Beam Position Monitors:
Detector Principle, Hardware and Electronics

Outline:

- *Signal generation → transfer impedance*
- *Consideration for capacitive shoe box BPM*
- *Consideration for capacitive button BPM*
- ***Other BPM principles: stripline → traveling wave***
  inductive → wall current
  cavity → resonator for dipole mode
- ***Electronics for position evaluation***
- ***Some examples for position evaluation and other applications***
- ***Summary***

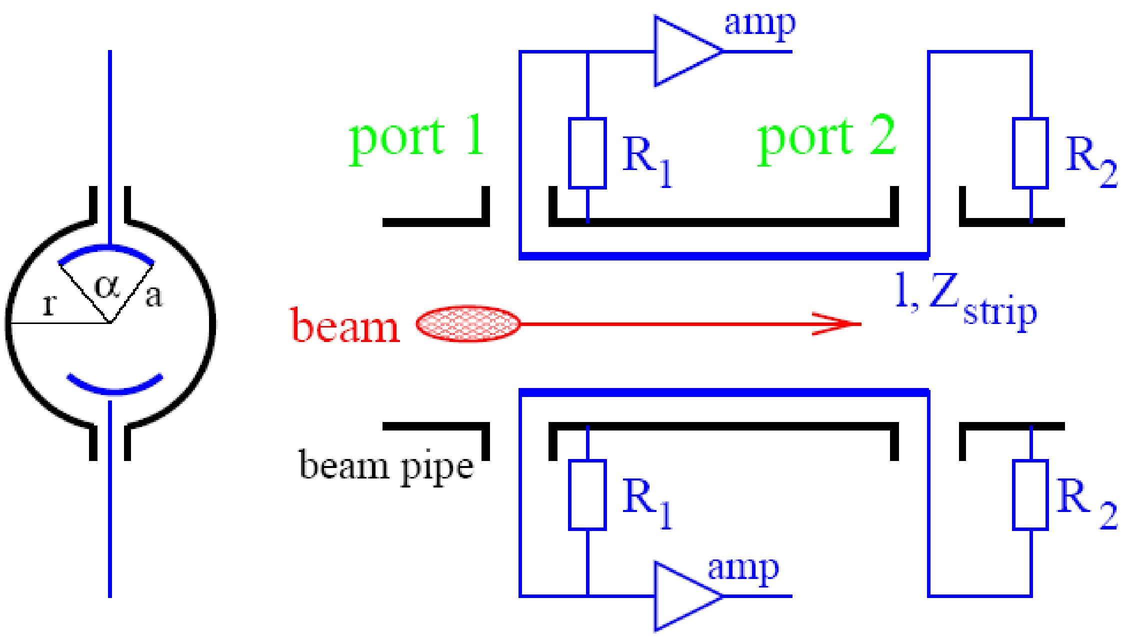
Stripline BPM: General Idea

For short bunches, the ***capacitive*** button deforms the signal

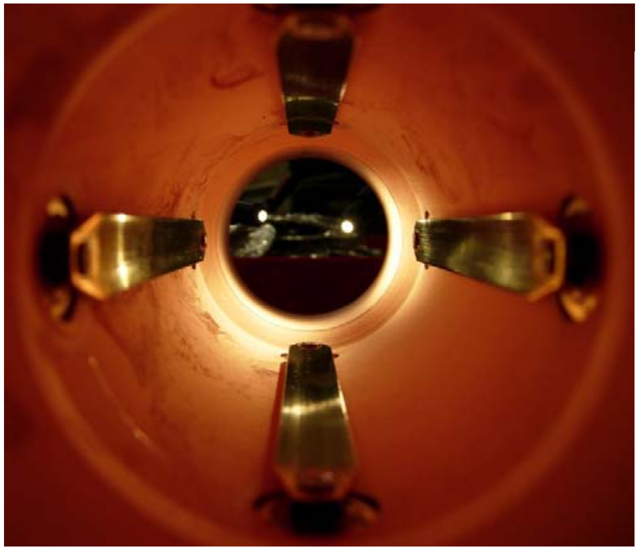
→ Relativistic beam ***β≈1*** ⇒ field of bunches nearly TEM wave

→ Bunch's electro-magnetic field induces a **traveling pulse** at the strips

→ Assumption: Bunch shorter than BPM, $Z_{strip}=R_1=R_2=50\ \Omega$ and $v_{beam}=c_{strip}$.



LHC stripline BPM, *l*=12 cm



From C. Boccard, CERN

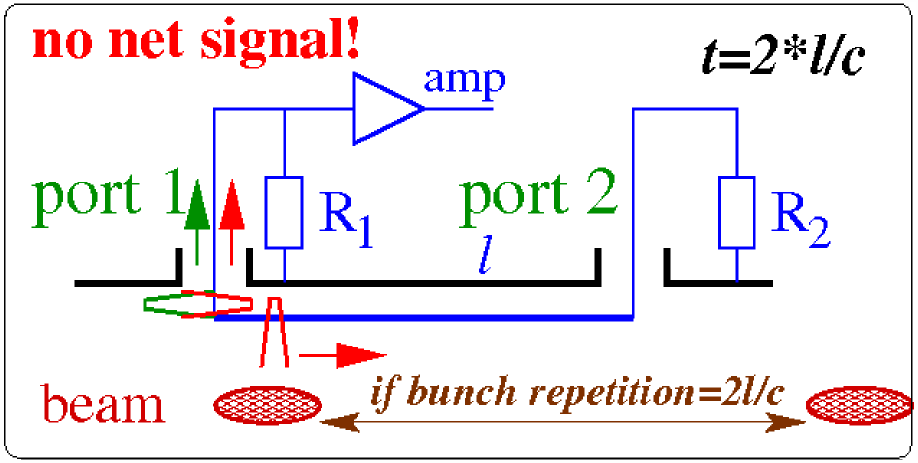
Stripline BPM: General Idea

For relativistic beam with ***β≈1*** and short bunches:

→ Bunch's electro-magnetic field induces a **traveling pulse** at the strip

→ ***Assumption:*** $l_{bunch} << l$, $Z_{strip}=R_1=R_2=50\ \Omega$ and $v_{beam}=c_{strip}$

Signal treatment at upstream port 1:



t=0: Beam induced charges at **port 1**:
→ half to ***R₁***, half toward **port 2**

t=l/c: Beam induced charges at **port 2**:
→ half to R_2, ***but*** due to different sign, it cancels with the signal from **port 1**
→ half signal reflected

t=2·l/c: reflected signal reaches **port 1**

$$\Rightarrow U_1(t)=\frac{1}{2}\cdot\frac{\alpha}{2\pi}\cdot Z_{strip}\left(I_{beam}(t)-I_{beam}(t-2l/c)\right)$$

If beam repetition time equals 2·l/c: reflected preceding port 2 signal cancels the new one:
→ no net signal at **port 1**

Signal at downstream port 2: Beam induced charges cancels with traveling charge from port 1

⇒ Signal depends direction ⇔ directional coupler: e.g. can distinguish between e^- and e^+ in collider

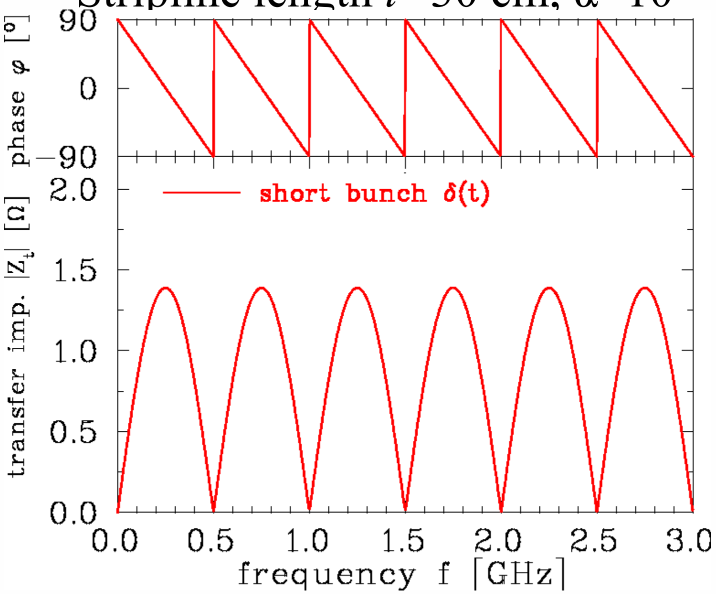
Stripline BPM: Transfer Impedance

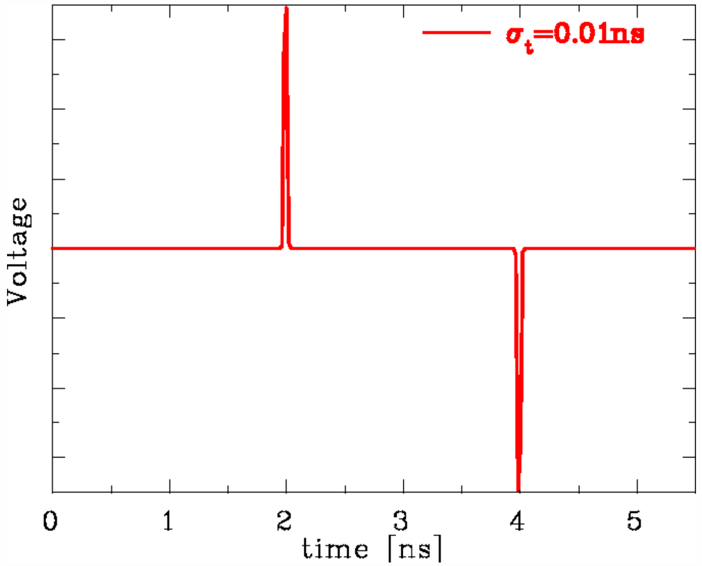
The signal from port 1 and the reflection from port 2 can cancel ⇒ minima in Z_t.

For short bunches $I_{beam}(t) \to Ne \cdot \delta(t)$:

$$Z_t(\omega) = Z_{strip} \cdot \frac{\alpha}{2\pi} \cdot \sin(\omega l / c) \cdot e^{i(\pi/2-\omega l/c)}$$

Stripline length l=30 cm, $\alpha=10^0$





- Z_t show maximum at $l=c/4f=\lambda/4$ i.e. ‘quarter wave coupler’ for bunch train
  ⇒ l has to be matched to v_{beam}
- No signal for $l=c/2f=\lambda/2$ i.e. destructive interference with **subsequent** bunch
- Around maximum of $|Z_t|$: phase shift $\varphi=0$ i.e. direct image of bunch
- $f_{center}=1/4 \cdot c/l \cdot (2n-1)$. For first lope: $f_{low}=1/2 \cdot f_{center}$, $f_{high}=3/2 \cdot f_{center}$ i.e. bandwidth $\approx 1/2 \cdot f_{center}$
- Precise matching at feed-through required t o preserve 50 Ω matching.

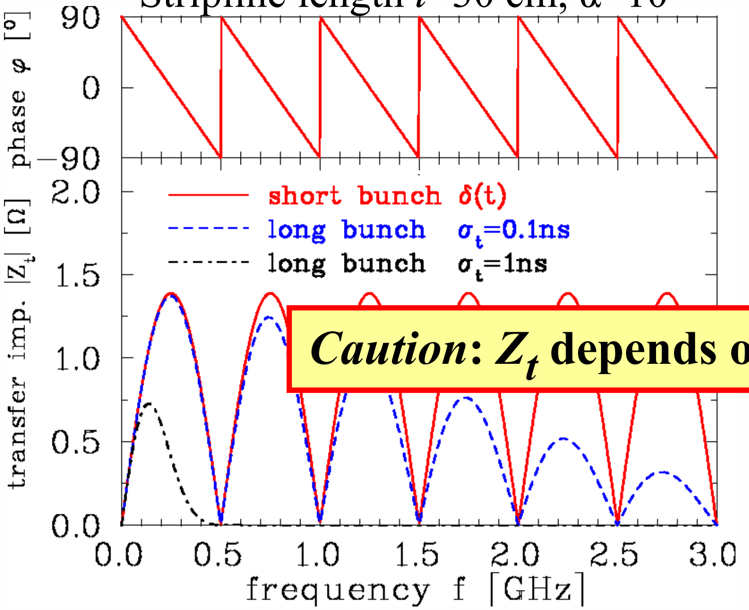
Stripline BPM: Finite Bunch Length

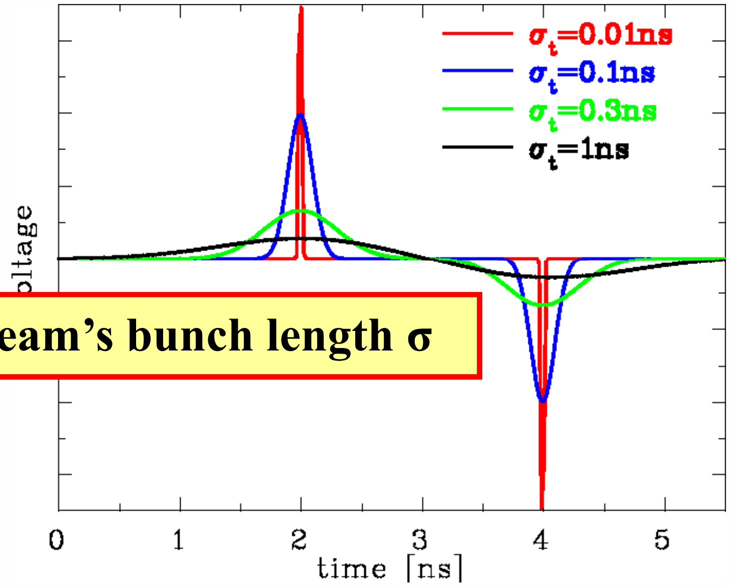
The signal at port 1 for a finite bunch of length σ: $I_{beam}(t) = I_0 \cdot e^{-t^2/2\sigma^2}$

$$\Rightarrow Z_t(\omega) = Z_{strip} \cdot \frac{\alpha}{2\pi} \cdot e^{-\omega^2\sigma^2/2} \cdot \sin(\omega l/c) \cdot e^{i(\pi/2-\omega l/c)}$$

$$\Rightarrow \text{in time domain}: U_{im}(t) = Z_{strip} \cdot \frac{\alpha}{2\pi} \cdot \left(e^{-(t+l/c)^2/2\sigma^2} - e^{-(t-l/c)^2/2\sigma^2}\right) \cdot I_0$$

Stripline length l=30 cm, α=10^0



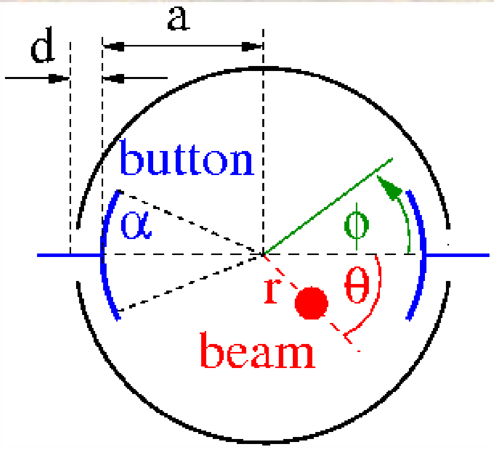


***Caution*: Z_t depends on beam's bunch length σ**

- $Z_t(\omega)$ decreases for higher frequencies
- If total bunch is too long ($\pm 3\sigma_t > l$) destructive interference leads to signal damping

  Cure: length of stripline has to be matched to bunch length

2-dim Model for Stripline BPM

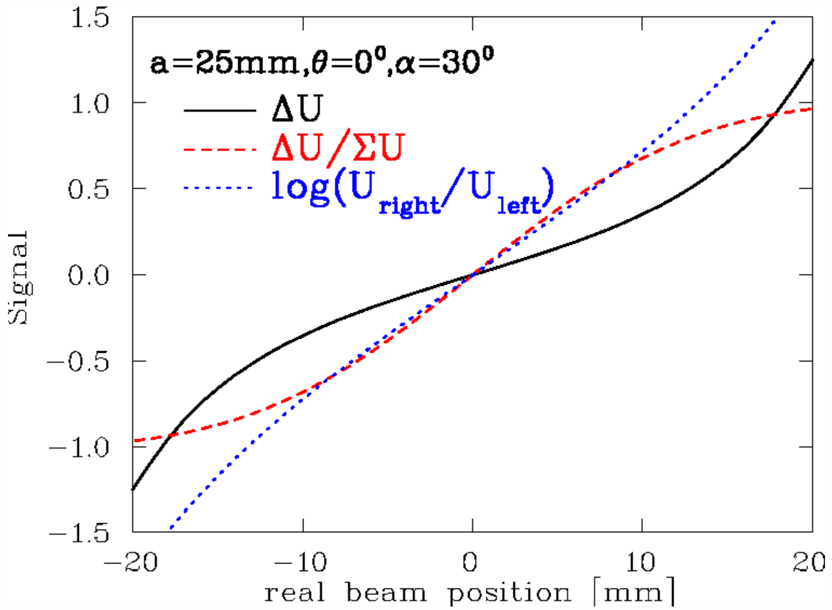


'Proximity effect': larger signal for closer plate

2-dim case: Cylindrical pipe → image current density:

$$j_{im}(\phi) = \frac{I_{beam}}{2\pi a} \cdot \left(\frac{a^2 - r^2}{a^2 + r^2 - 2ar \cdot \cos(\phi - \theta)} \right)$$

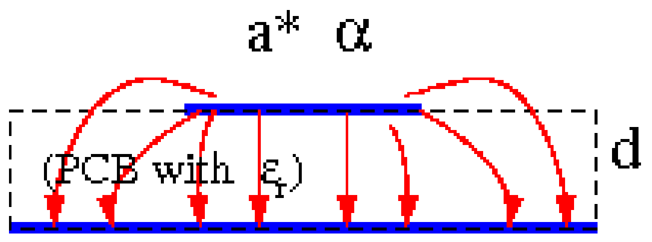
Image current of finite BPM size: $I_{im} = a \cdot \int_{-\alpha/2}^{\alpha/2} j_{im}(\phi) d\phi$



Impedance Z_{strip}=50Ω:

Comparable formula as for PCB micro-strip

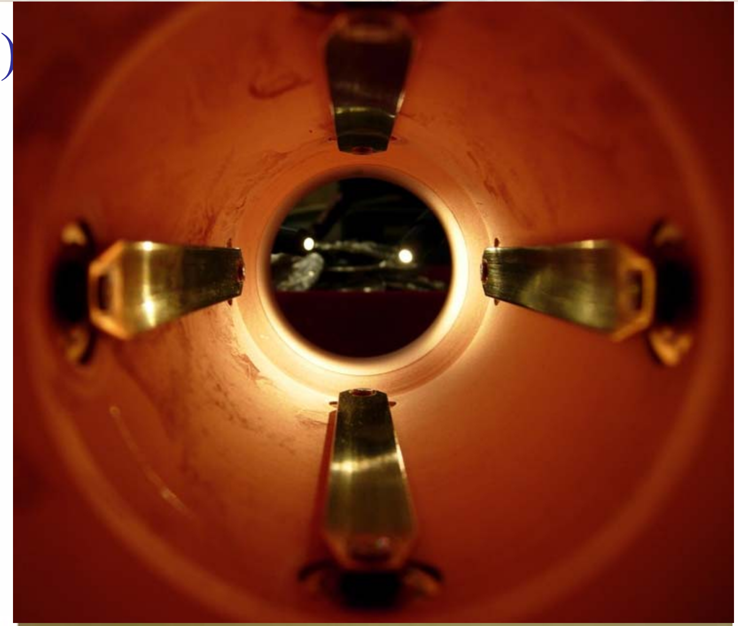
→dependence on *d* and α

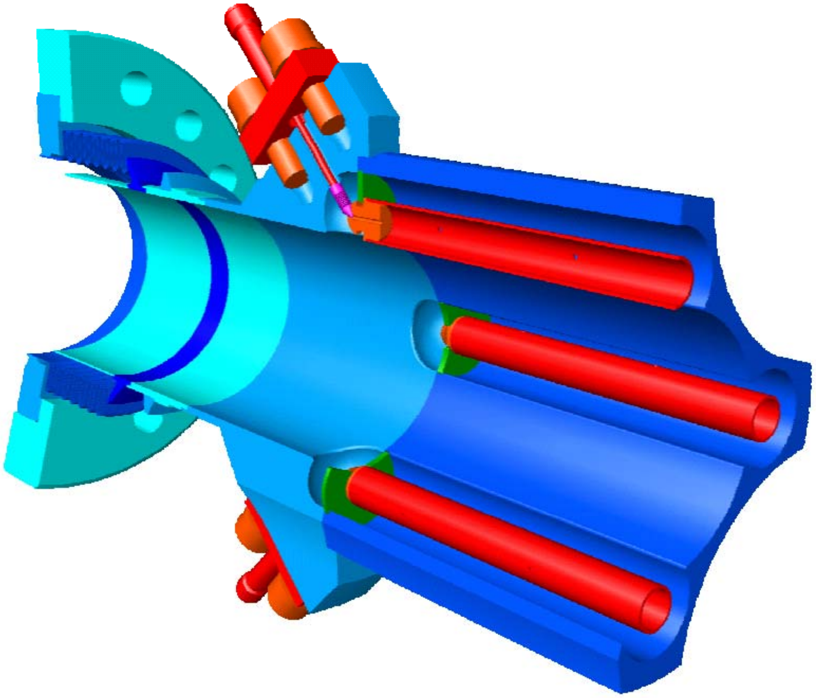


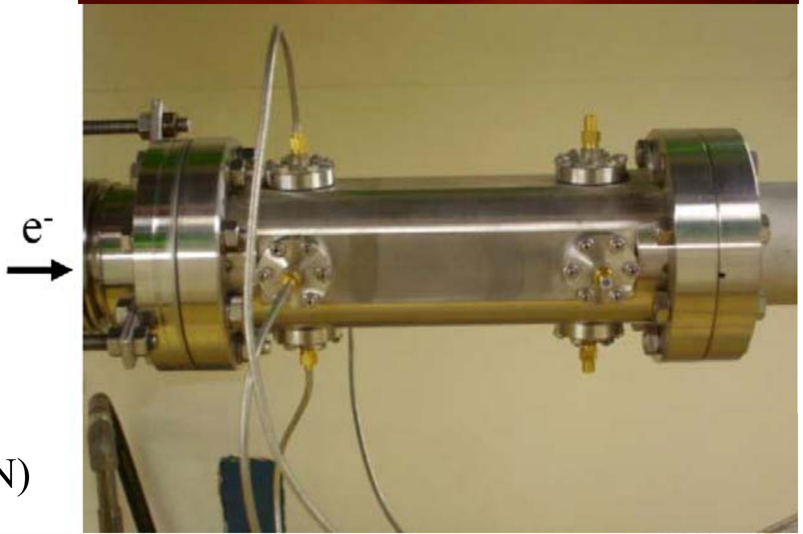
Realization of Stripline BPM

20 cm stripline BPM at TTF2 (chamber ∅34mm)

And 12 cm LHC type:





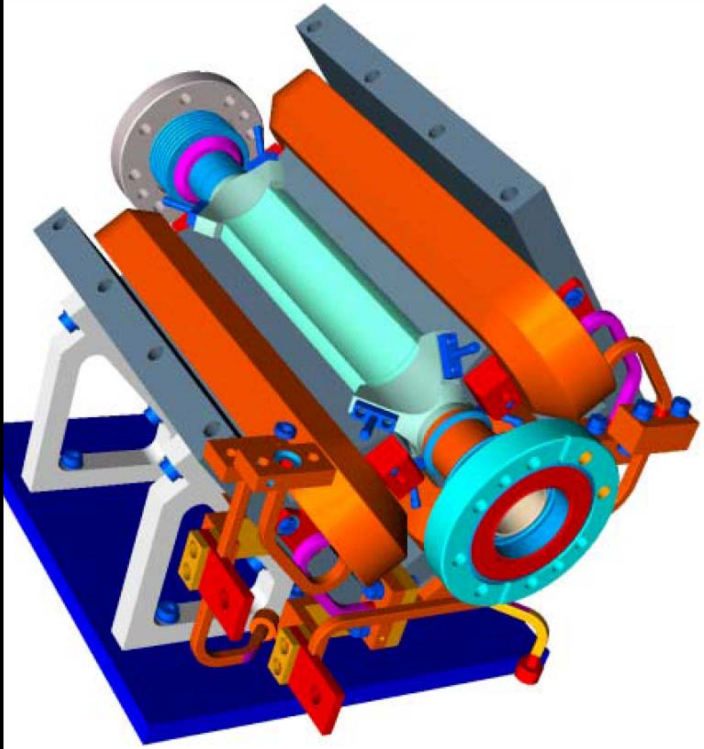


From . S. Wilkins, D. Nölle (DESY), C. Boccard (CERN)

Comparison: Stripline and Button BPM (simplified)

	Stripline	**Button**
Idea	traveling wave	electro-static
Requirement	Careful $Z_{strip}=50\Omega$ matching	
Signal quality	Less deformation of bunch signal	Deformation by finite size and capacitance
Bandwidth	Broadband, but minima	Highpass, but f_{cut}<1 GHz
Signal strength	Large Large longitudinal and transverse coverage possible	Small Size <∅3cm, to prevent signal deformation
Mechanics	Complex	Simple
Installation	Inside quadrupole possible ⇒improving accuracy	Compact insertion
Directivity	**YES**	No

TTF2 BPM inside quadrupole



From . S. Wilkins,
D. Nölle (DESY)

Resistive Wall Current Monitor

Broadband observation of bunches can be performed with a resistive Wall Current Monitor

Principle: ► Ceramic gap bridged with n=10…100 resistors of R=10…100 Ω

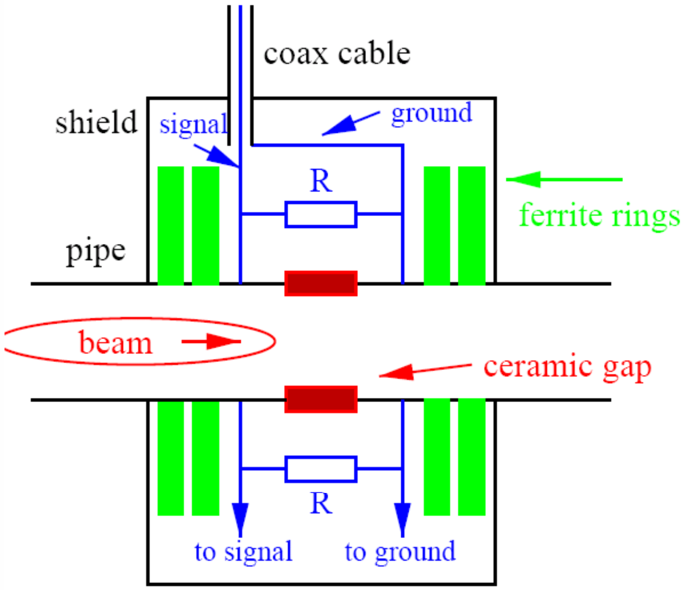
► Measurement of voltage drop for $R_{tot}=1/n\cdot R$=1…10 Ω

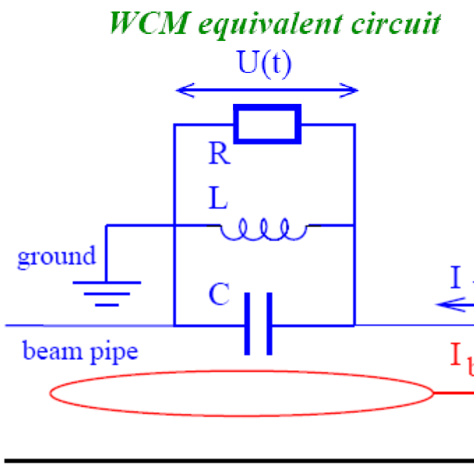
► Ferrit rings with high → forces low frequency components through R

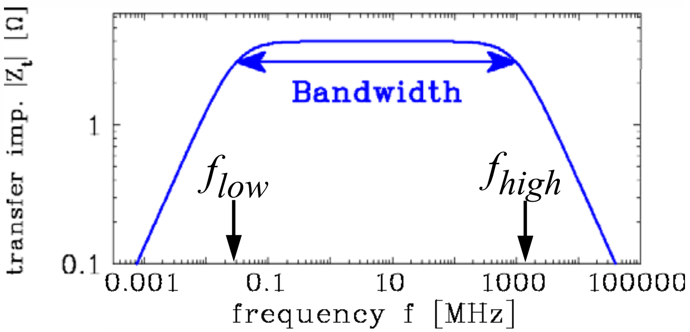
Bandwidth: typically $f_{low}=R/(2\pi L)\approx$ **10 kHz**

$f_{high}=1/(2\pi R_{tot}C)\approx$ **1 GHz**

Application: Broadband bunch observation





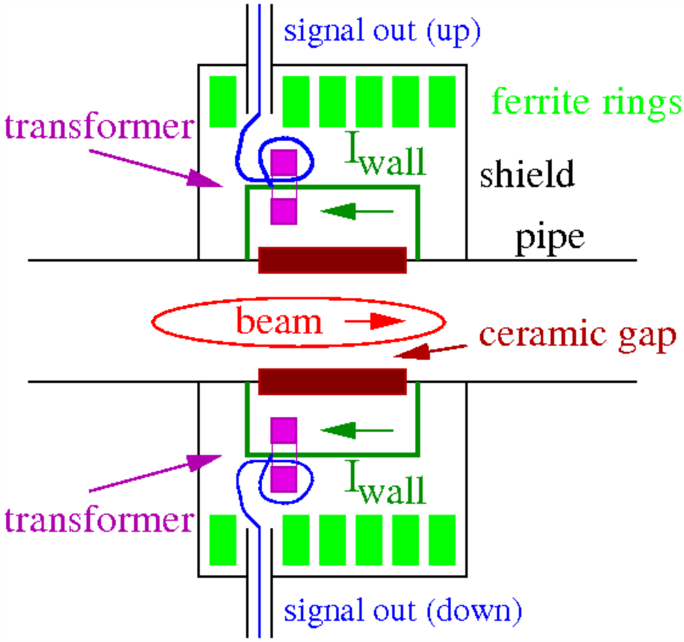


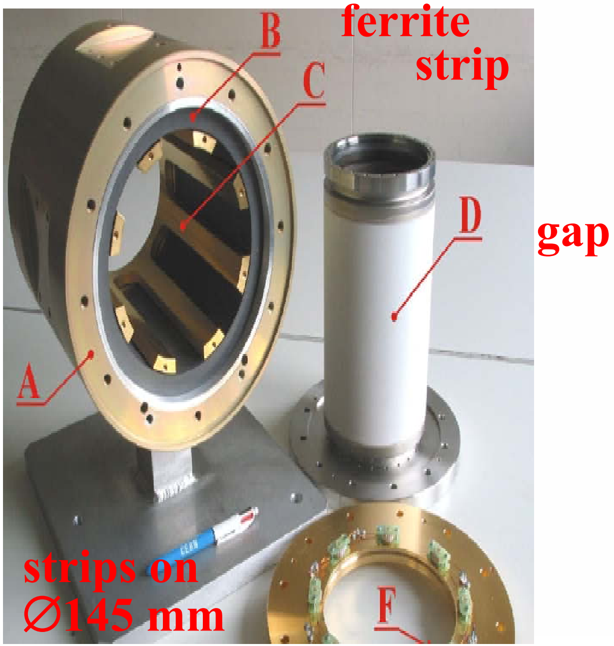
$$\frac{1}{Z_t}=\frac{1}{R_{tot}}+\frac{1}{i\omega L}+i\omega C$$

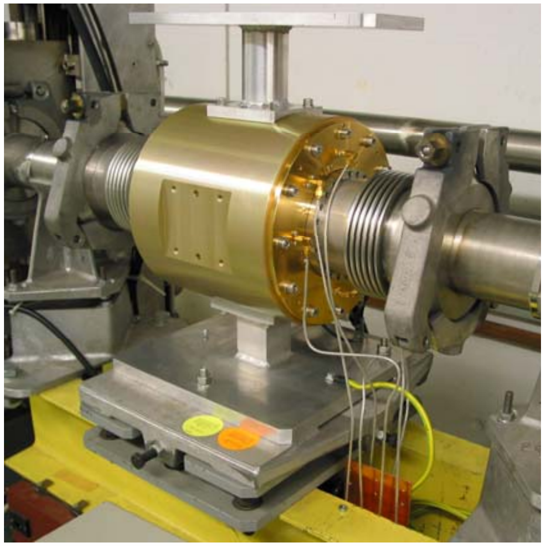
Within bandwidth: $Z_t \cong R_{tot}$

Inductive Wall Current Monitor

The wall current is passed through strips and is determined be transformers.







From M.Gasior (CERN), DIPAC 2003 & 2005

Example: CERN **CTF3** and LINAC2 device

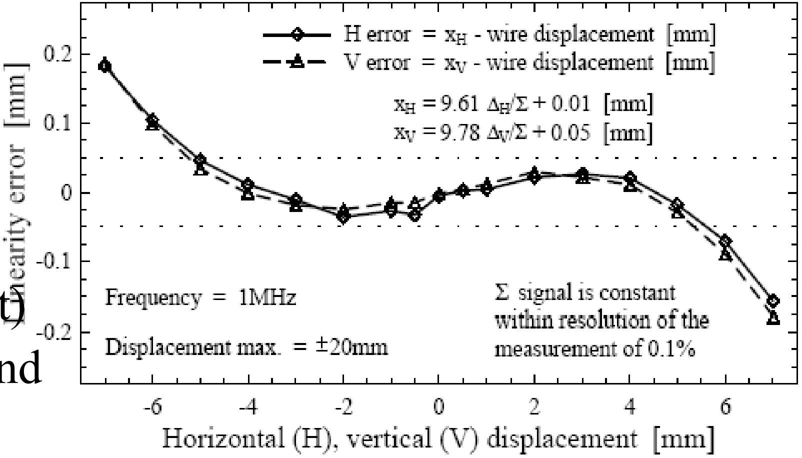
Parameters: 8 strips on ∅50 mm

for CFT3 Bandwidth: 300 kHz to 250 MHz

Transfer impedance: Z_t=10 Ω

Sensitivity: S=10 %/mm (central part)

Advantage: Everything outside vacuum, broadband



Cavity BPM

High resolution on µs time scale can be achieved by excitation of a dipole mode:

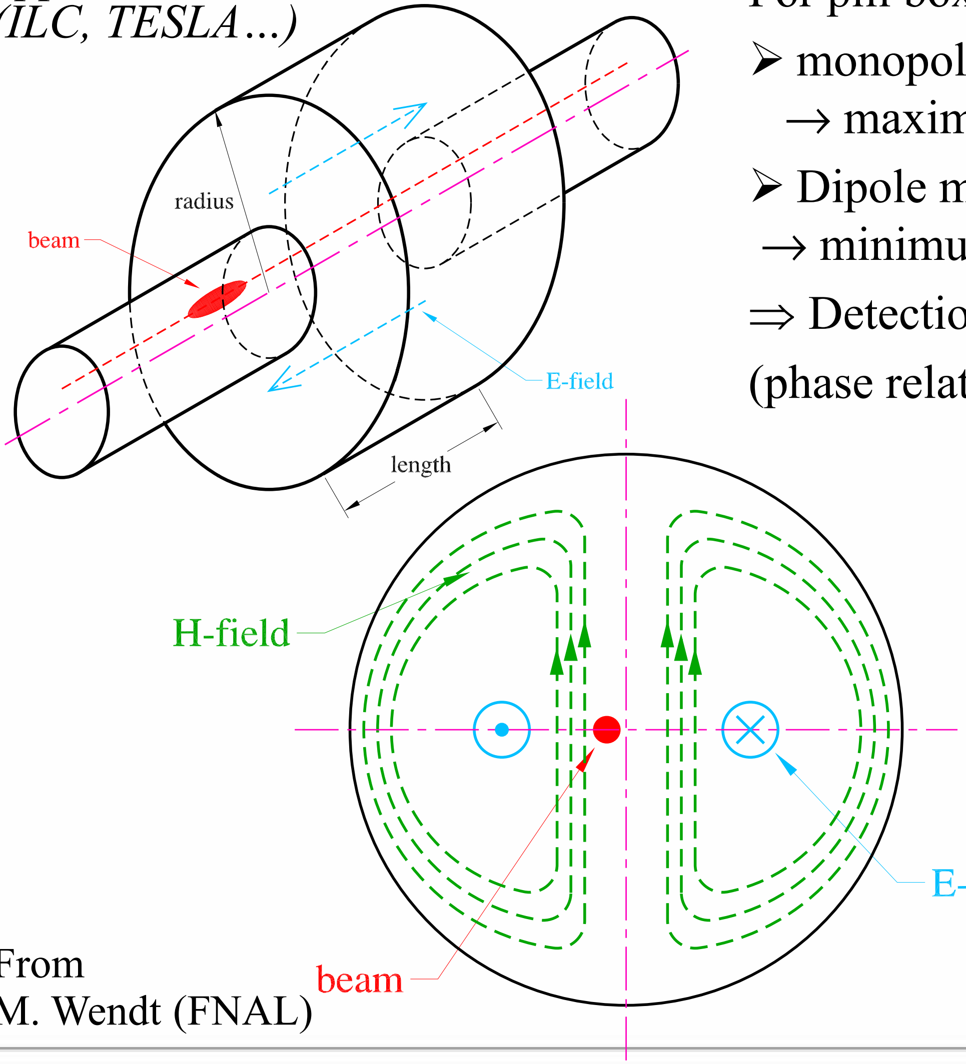
Application: small e⁻ beams
(ILC, TESLA…)

For pill box the resonator modes given by geometry:

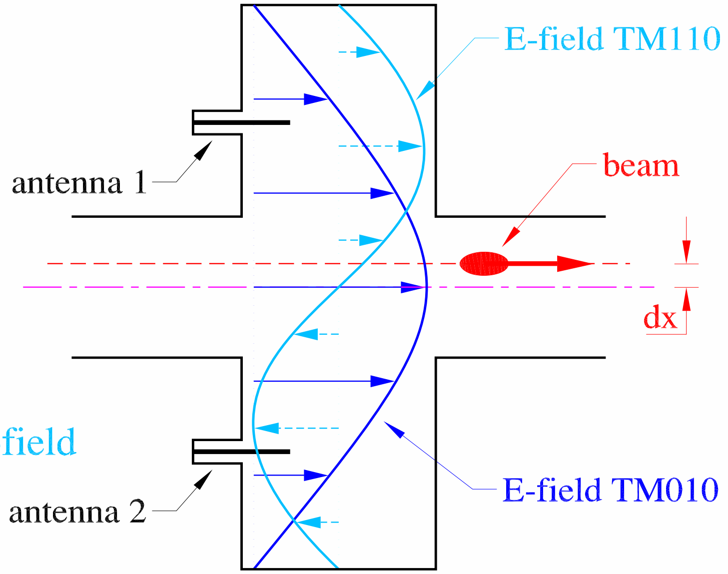
- ➢ monopole TM_{010} with $\boldsymbol{f_{010}}$
  → maximum at beam center ⇒ strong excitation
- ➢ Dipole mode TM_{011} with $\boldsymbol{f_{011}}$
  → minimum at center ⇒ excitation by beam offset

⇒ Detection of dipole mode amplitude

(phase relative to monopole gives sign of displacement)



From
M. Wendt (FNAL)



Cavity BPM

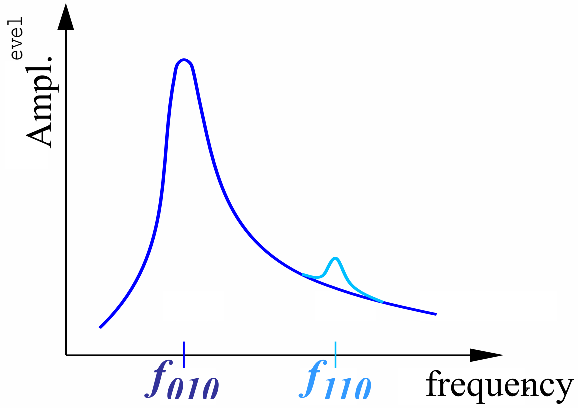
Basic consideration for detection of eigen-frequency amplitudes:

Dipole mode f_{110} separated from monopole mode

due to finite quality factor $Q \Rightarrow \Delta f = f/Q$

- Waveguide house the antennas

  (task: suppression of TM_{010} mode signal)
- Frequency $f_{110} \approx 1 \ldots 10$ GHz



FNAL realization:

Cavity: ∅ 113 mm

Gap 15 mm

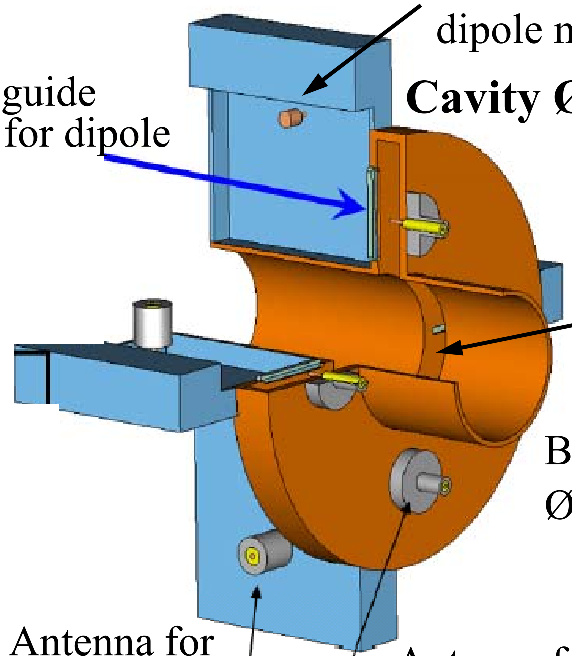
Mono. f_{010}=1.1GHz

Dipole. f_{110}=1.5GHz

$Q_{load} \approx 600$

With comparable BPM

⇒0.1 µm resolution within 1 µs



Antenna for dipole mode

Waveguide input for dipole mode

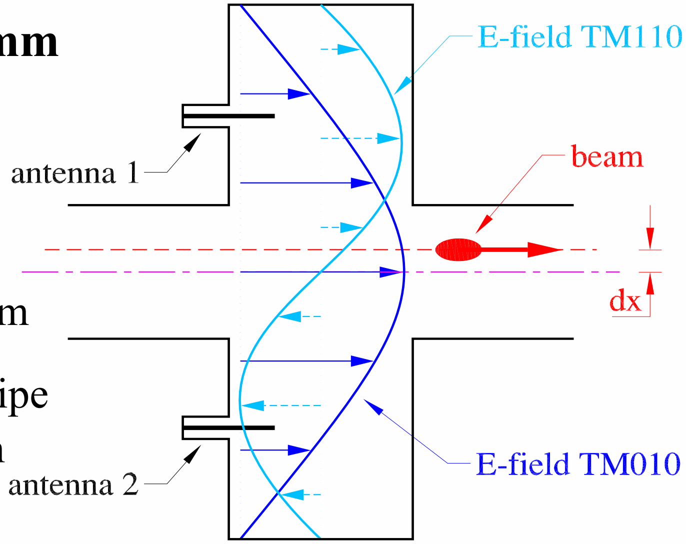
Cavity Ø113mm

Gap 15 mm

Beam pipe Ø39mm

Antenna for dipole mode

Antenna for monopole mode



From M. Wendt (FNAL)

Comparison of BPM Types (simplified)

Type	Usage	Precaution	Advantage	Disadvantage
Shoe-box	p-Synch.	Long bunches $f_{rf}<10$ MHz	Very linear No x-y coupling Sensitive For broad beams	Complex mechanics Capacitive coupling between plates
Button	p-Linacs, all e^- acc.	$f_{rf}>10$ MHz	Simple mechanics	Non-linear, x-y coupling Possible signal deformation
Stipline	colliders p-Linacs all e^- acc.	best for $\beta\approx1$, short bunches	Directivity 'Clean' signals Large Signal	Complex $50\ \Omega$ matching Complex mechanics
Ind. WCM	all	non	Broadband	Complex, long insertion
Cavity	e^- Linacs (e.g. FEL)	Short bunches Special appl.	Very sensitive	Very complex, high frequency

Remark: Other types are also some time used, e.g. inductive antenna based, BPMs with external resonator, slotted wave-guides for stochastic cooling etc.

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- *Other BPM principles: stripline → traveling wave*
  inductive → wall current
  cavity → resonator for dipole mode
- ***Electronics for position evaluation***
  Noise consideration, broadband and narrowband analog processing, digital processing
- ***Some examples for position evaluation and other applications***
- ***Summary***

Characteristics for Position Measurement

Position sensitivity: Factor between beam position & signal quantity ($\Delta U/\Sigma U$ or $\log U_1/U_2$)

defined as $S_x(x,y,f) = \frac{d}{dx}\left(\Delta U_x / \Sigma U_x\right) = [\%/\text{mm}]$

Accuracy: Ability for position reading relative to a mechanical fix-point ('absolute position')

- influenced by mechanical tolerances and alignment accuracy and reproducibility
- by electronics: e.g. amplifier drifts, electronic interference, ADC granularity

Resolution: Ability to determine small displacement variation ('relative position')

- typically: ***single bunch***: 10^{-3} of aperture ≈ 100 µm
  averaged: 10^{-5} of aperture ≈1 µm, with dedicated methods ≈0.1 µm
- in most case much better than accuracy!
- electronics has to match the requirements e.g. bandwidth, ADC granularity…

Bandwidth: Frequency range available for measurement

- has to be chosen with respect to required resolution via analog or digital filtering

Dynamic range: Range of beam currents the system has to respond

- position reading should not depend on input amplitude

Signal-to-noise: Ratio of wanted signal to unwanted background

- influenced by thermal and circuit noise, electronic interference
- can be matched by bandwidth limitation

Signal sensitivity = detection threshold: minimum beam current for measurement

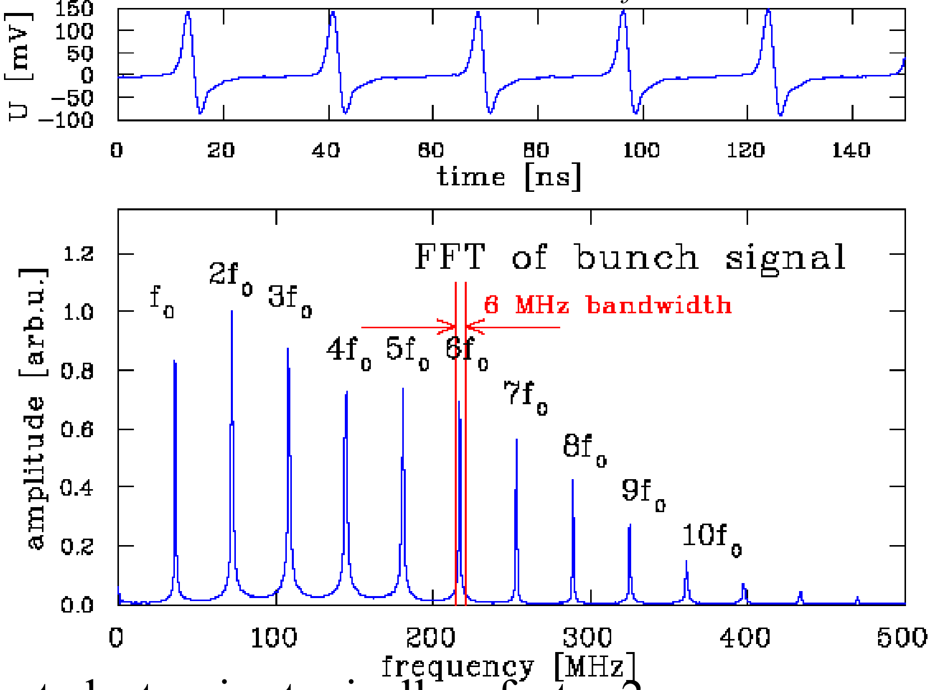
General: Noise Consideration

1. Signal voltage given by: $U_{im}(f) = Z_t(f) \cdot I_{beam}(f)$
2. Position information from voltage difference: $x = 1/S \cdot \Delta U / \Sigma U$
3. Thermal noise voltage given by: $U_{eff}(R, \Delta f) = \sqrt{4k_B \cdot T \cdot R \cdot \Delta f}$

⇒ Signal-to-noise $\Delta U_{im}/U_{eff}$ is influenced by:

- ➢ Input signal amplitude
  → large or matched Z_t
- ➢ Thermal noise at $\boldsymbol{R}$=50Ω for $\boldsymbol{T}$=300K
  (for shoe box $\boldsymbol{R}$=1kΩ …1MΩ)
- ➢ Bandwidth $\boldsymbol{\Delta f}$
  ⇒ Restriction of frequency width because the power is concentrated on the harmonics of $\boldsymbol{f_{rf}}$

Example: GSI-LINAC with f_{rf}=36 MHz



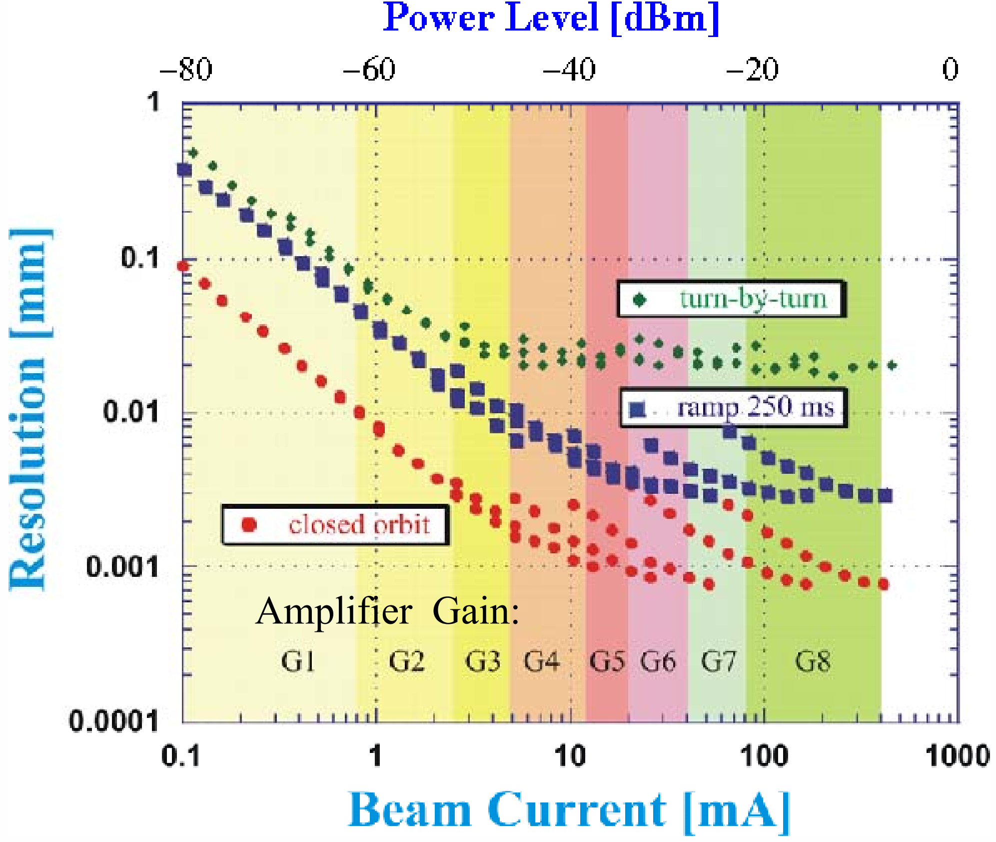
Remark: Additional contribution by non-perfect electronics typically a factor 2

Moreover, pick-up by electro-magnetic interference can contribute ⇒ good shielding required

Example for Noise Consideration

1. Signal voltage given by: $U_{im}(f) = Z_t(f) \cdot I_{beam}(f)$
2. Thermal noise voltage given by: $U_{eff}(R, \Delta f) = \sqrt{4k_B \cdot T \cdot R \cdot \Delta f}$
3. Signal-to-noise ratio has to be calculated and expressed in spatial resolution σ

Example: *button BPM resolution at Synchrotron Light Source SLS at PSI:*



Bandwidth:

Turn-by turn = 500 kHz

Ramp 250 ms = 15 kHz

Closed orbit = 2 kHz

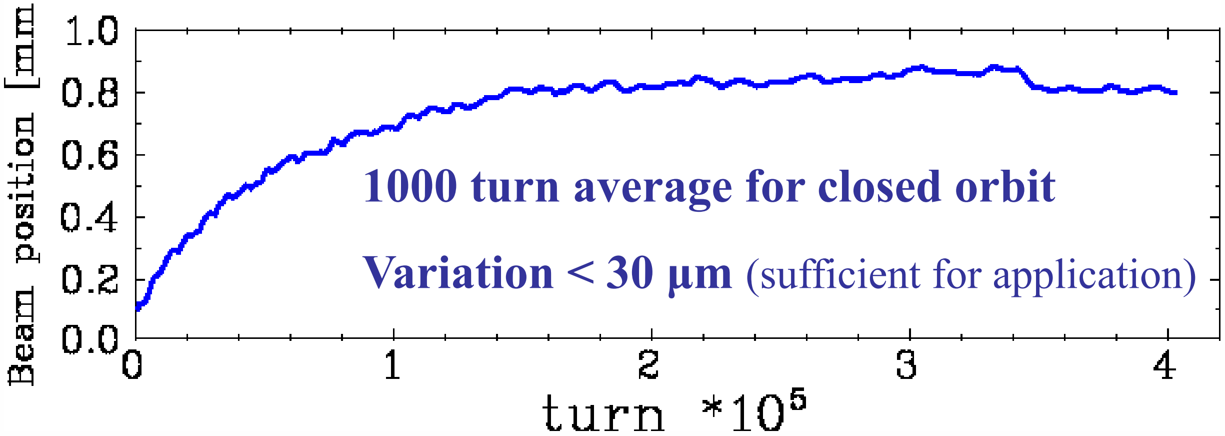
Result:

- **Slow readout** ⇔ low *Δf*
  ⇒ low *σ* due to $\sigma \propto \sqrt{\Delta f}$
- **Low current** ⇔ low signal
  ⇒ input noise dominates

From V. Schlott et al. (PSI) DIPAC 2001, p. 69

Comparison: Filtered Signal ↔ Single Turn

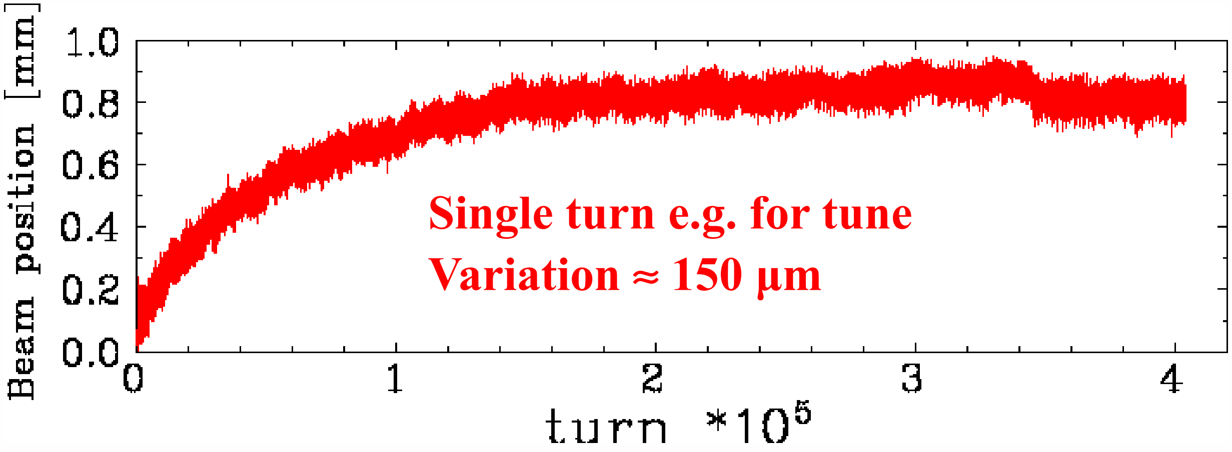
Example GSI Synchr.: U^{73+}, E_{inj}=11.5 MeV/u→ 250 MeV/u within 0.5 s, 10^9 ions



1000 turn average for closed orbit

Variation < 30 µm (sufficient for application)

- Position resolution < 30 µm (BPM half aperture *a*=90 mm)
- average over 1000 turns corresponding to ≈1 ms or ≈1 kHz bandwidth



Single turn e.g. for tune

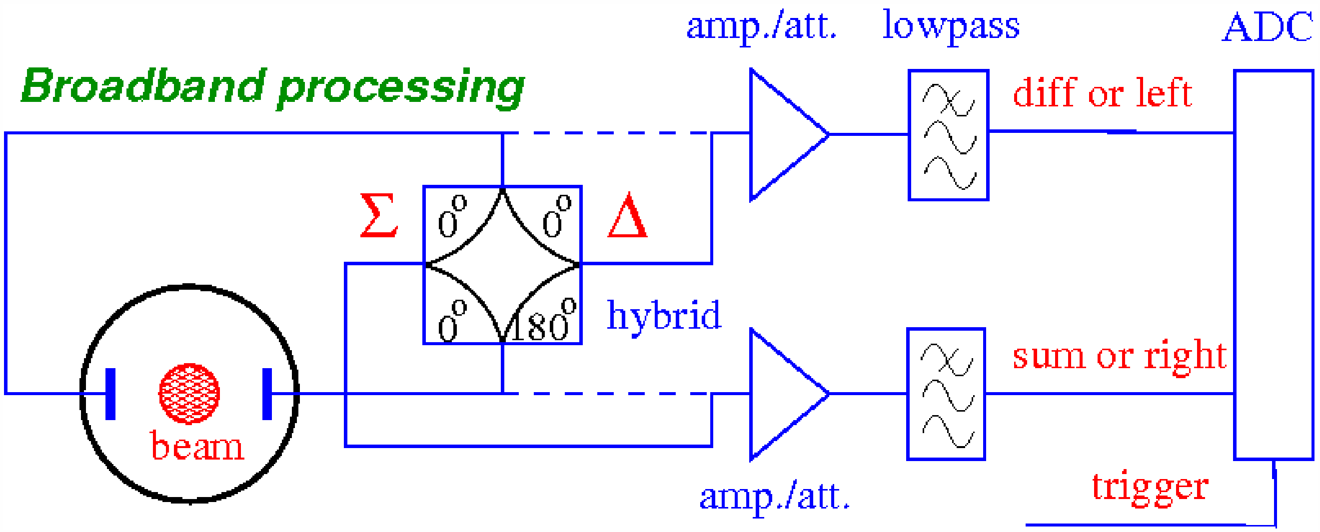
Variation ≈ 150 µm

- Turn-by-turn data have much larger variation

However: not only noise contributes but additionally **beam movement** by betatron oscillation

⇒ broadband processing i.e. turn-by-turn readout for tune determination

General Idea: Broadband Processing

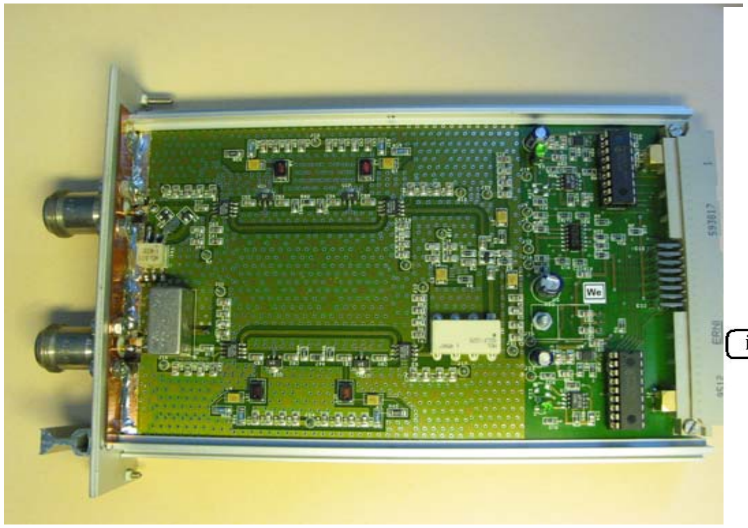


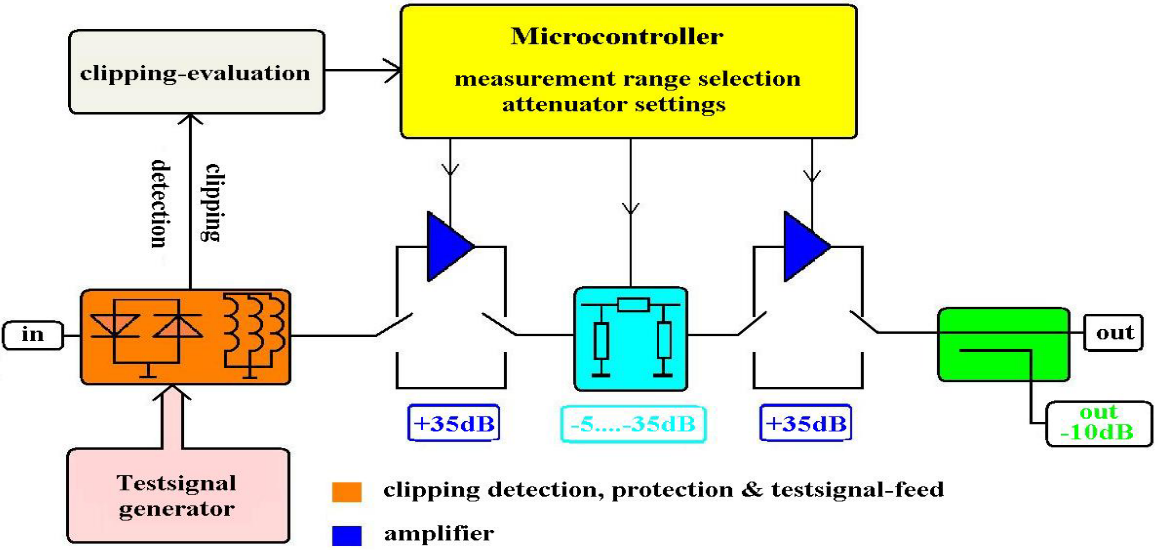
- ➢ Hybrid or transformer close to beam pipe for analog ΔU & ΣU generation or U_{left} & U_{right}
- ➢ Attenuator/amplifier
- ➢ Filter to get the wanted harmonics and to suppress stray signals
- ➢ ADC: digitalization ⟶ followed by calculation of of $\Delta U / \Sigma U$

Advantage: Bunch-by-bunch possible, versatile post-processing possible

Disadvantage: Resolution down to ≈ 100 μm for shoe box type , i.e. ≈0.1% of aperture,
resolution is worse than narrowband processing

Linear Amplifier with large dynamic Range for p-Synchrotron





🟧 clipping detection, protection & testsignal-feed

🟦 amplifier

🟦 variable attenuator

🟩 10 dB directional coupler

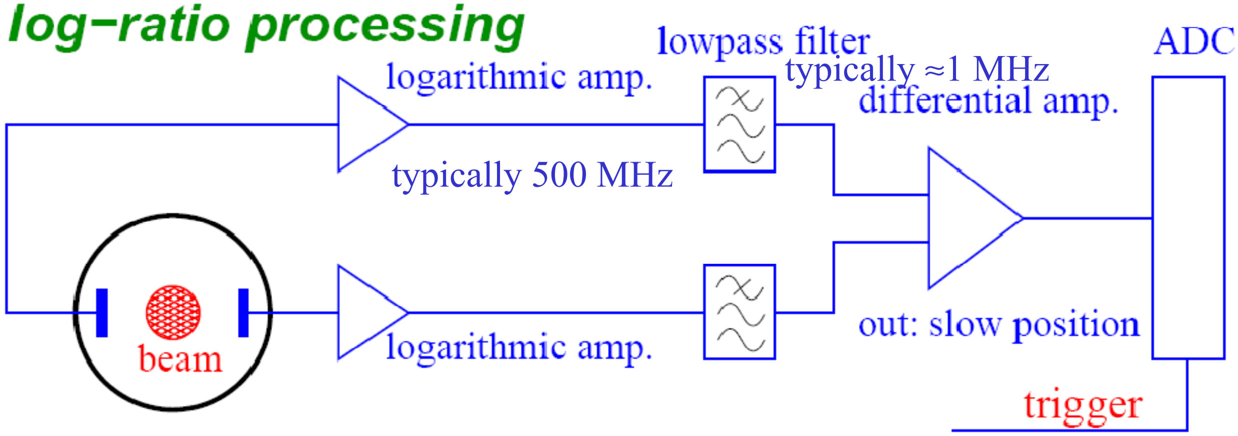
Example: pre-amp from GSI-synchrotron:

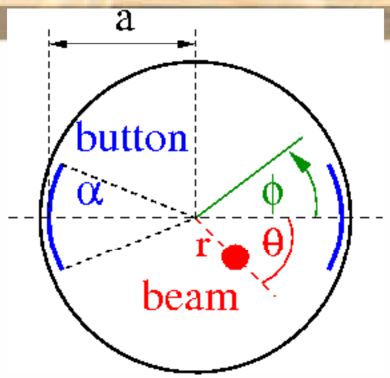
Shoe box BPM → matching 2:12 transformer R_{prim}=1.8kΩ→ ≈3 m cable → amplifier

- Requirement: Dynamic range from 1×10^8 to 4×10^{13} charges per bunch
  ⇒ 120dB dynamic range of signal amplitude
- Switchable 35dB amplifier stages, bandwidth 0.2 to 100 MHz.
- Variable PIN-diode attenuator -5dB…-35dB.
- Test generator input for control of constant gain and temperature drift calibration
- Common mode gain matching better than 0.1dB each BPM-plate pair for large accuracy

Logarithmic Amplifier Schematics

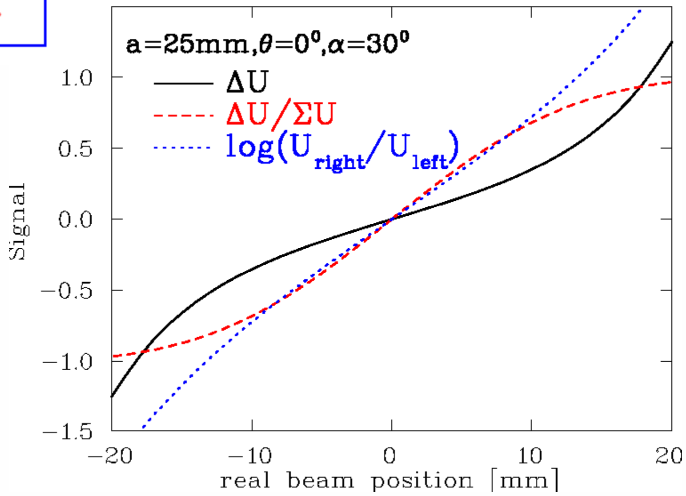
log-ratio processing





Input -80..0dBm
Max. 500 MHz

- Signal is ‘compressed’ by a logarithmic amplifier, filtered and applied to a differential amplifier.
- Typical video bandwidth ≈1MHz
- Position: $x = 1/S \cdot [\log(A) - \log(B)] = 1/S \cdot [\log(A/B)]$

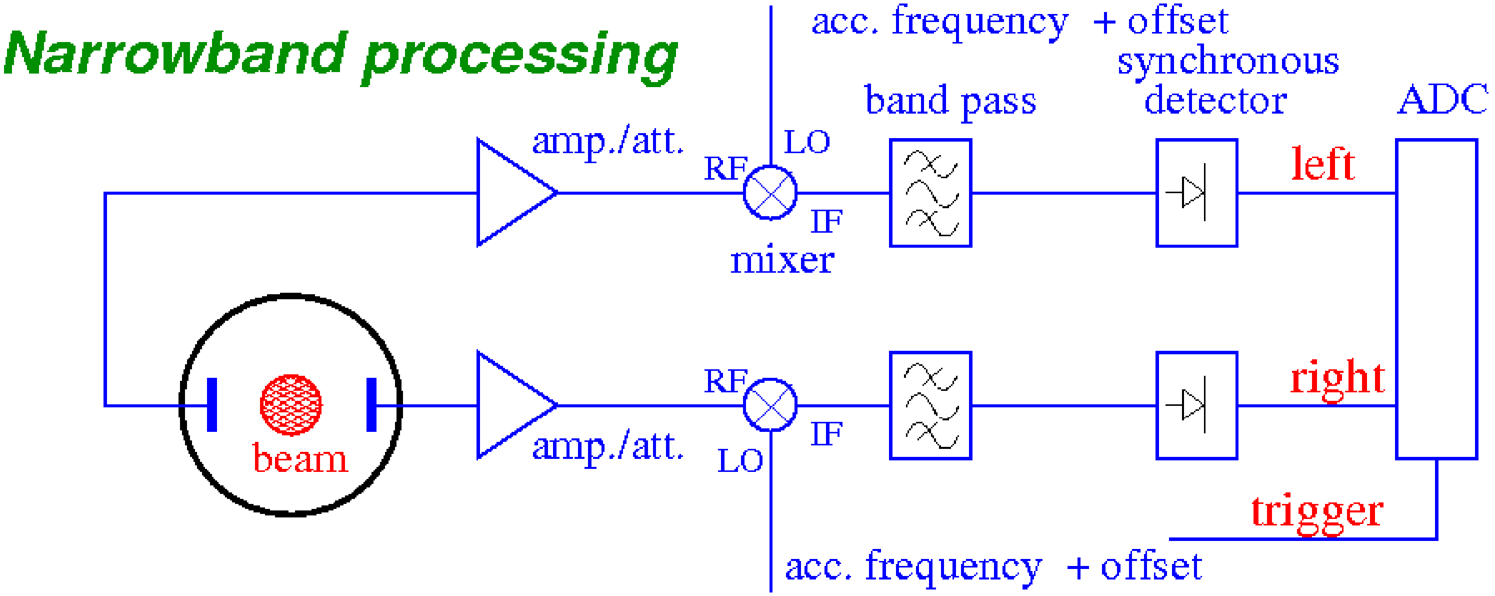


Advantage: Improved linearity for button, broadband robust electronics, large ≈90 dB dynamics range without gain switching

Disadvantage: limited linearity and accuracy, possible temperature dependence

Remark: Usage e.g. at transfer lines (which require less resolution)
Log-amp card ready for BPM usage is commercially available!

General Idea: Narrowband Processing



Narrowband processing equals heterodyne receiver (e.g. AM-radio or spectrum analyzer)

- ➢ Attenuator/amplifier
- ➢ Mixing with accelerating frequency $f_{rf} \Rightarrow$ signal with sum and difference frequency
- ➢ Bandpass filter of the mixed signal (e.g at 10.7 MHz)
- ➢ Rectifier: synchronous detector
- ➢ ADC: digitalization ⟶ followed calculation of $\Delta U/\Sigma U$

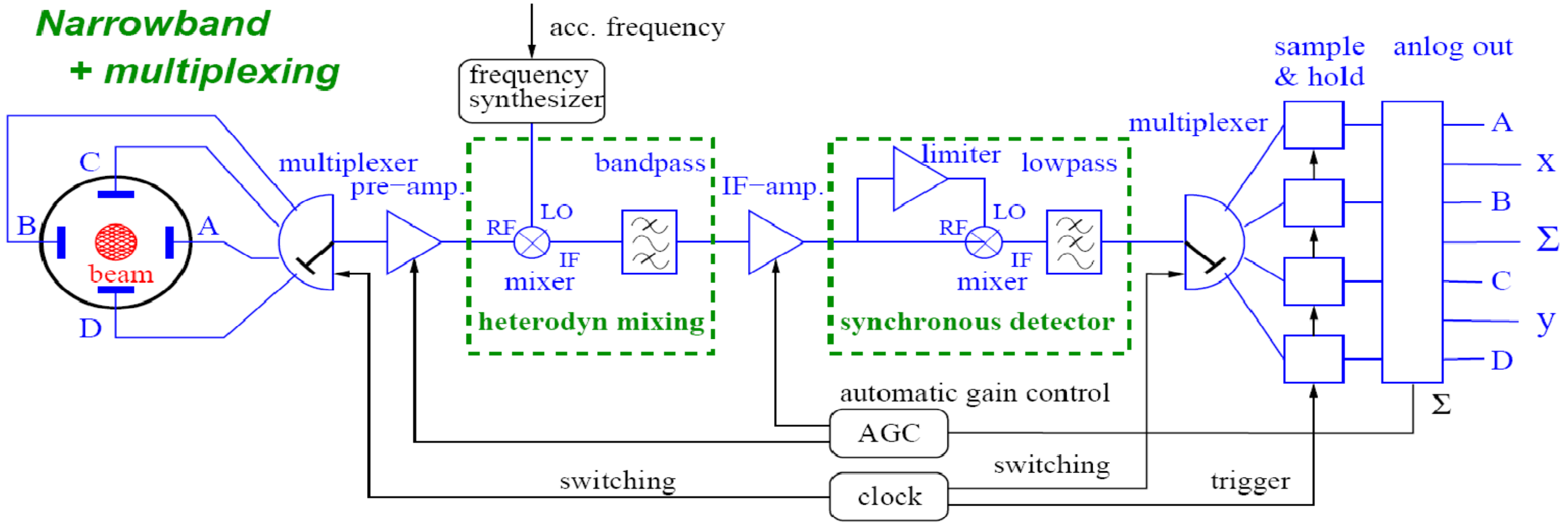
Advantage: spatial resolution about 100 time better than broadband processing.

Disadvantage: No turn-by-turn diagnosis, due to mixing = 'long averaging time'

For non-relativistic p-synchrotron: → variable f_{rf} leads via mixing to constant intermediate freq.

Narrowband Processing with Multiplexing

Dedicated analog electronics for narrowband processing on one card (commercially available):



Idea: narrowband processing, all buttons at **same** path ⇒ multiplexing of single electronics chain

Multiplexing within ≈0.1ms: ⇒ only one button is processed ⇒ minimal drifts contribution

Processing chain: Buttons → multiplexer → linear amplifier with fine gain steps by AGC
→ mixing with f_{rf} → narrow intermediate frequency filter BW 0.1 ….1 MHz
→ synchronous detector for rectification → de-multiplexer → slow and precise ADC

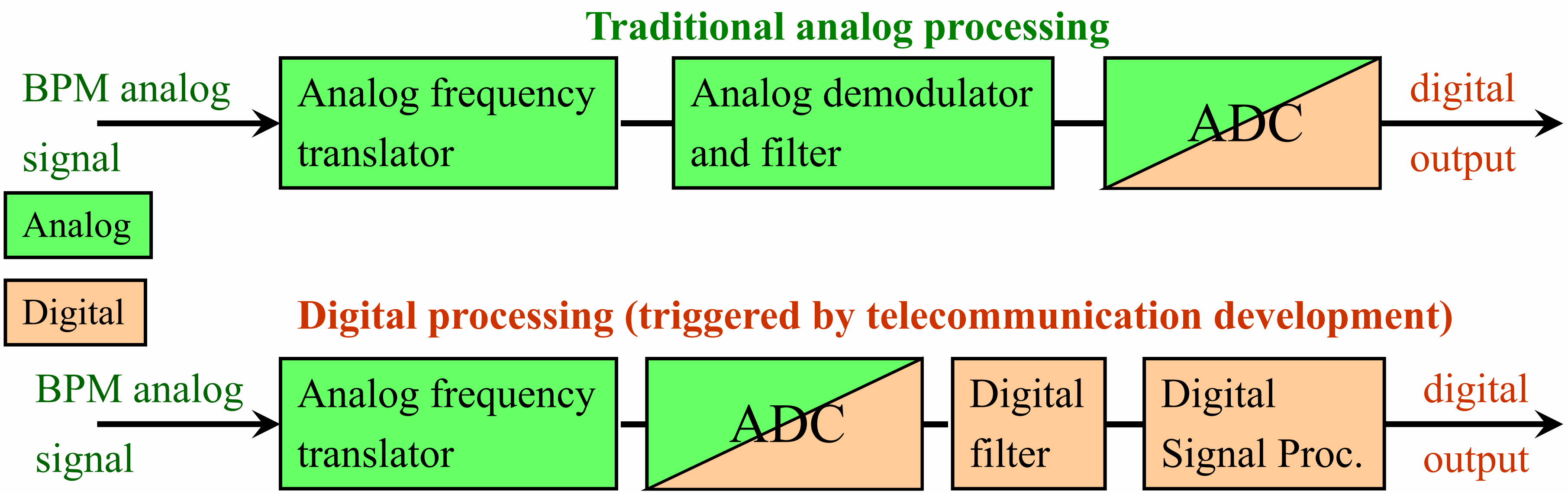
Advantage: High accuracy, high resolution, high dynamic range by automated gain control AGC

Disadvantage: Multiplexing ⇒ only for stable beams >> 10 ms, narrowband ⇒ no turn-by-turn

Remark: 'Stable' beam e.g. at synch. light source, but not at accelerating synchrotrons!

Analog versus Digital Signal Processing

Modern instrumentation uses **digital** techniques with extended functionality.



Traditional analog processing

BPM analog signal

Analog frequency translator

Analog demodulator and filter

ADC

digital output

🟩 Analog

🟧 Digital

Digital processing (triggered by telecommunication development)

BPM analog signal

Analog frequency translator

ADC

Digital filter

Digital Signal Proc.

digital output

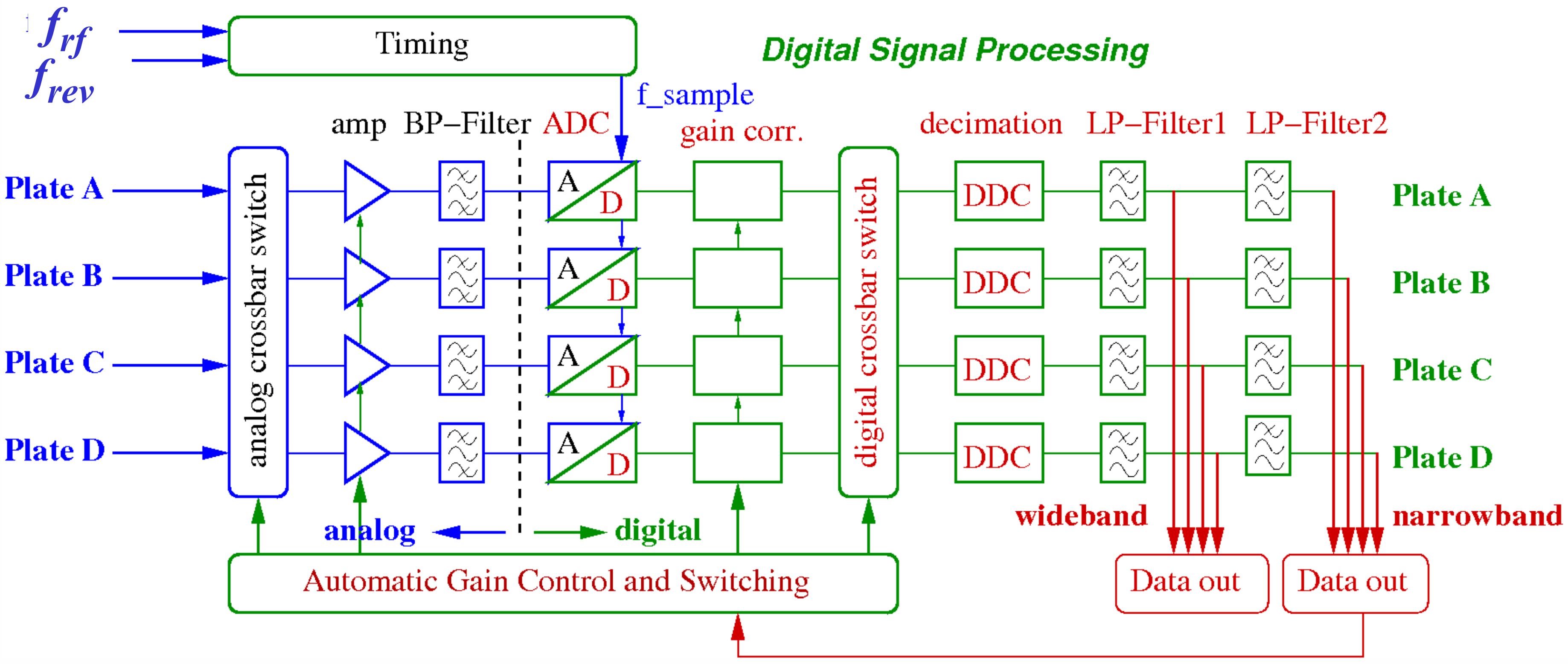
Digital receiver as modern successor of heterodyne receiver

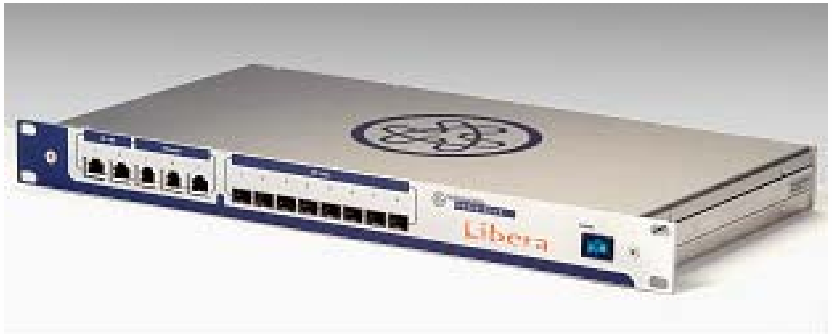
- Basic functionality is preserved but implementation is very different
- Digital transition just after the amplifier&filter or mixing unit
- Signal conditioning (filter, decimation, averaging) on FPGA

Advantage of DSP: Stable operation, flexible adoption without hardware modification

Disadvantage of DSP: non, good engineering skill requires for development, expensive

Digital Signal Processing Realization



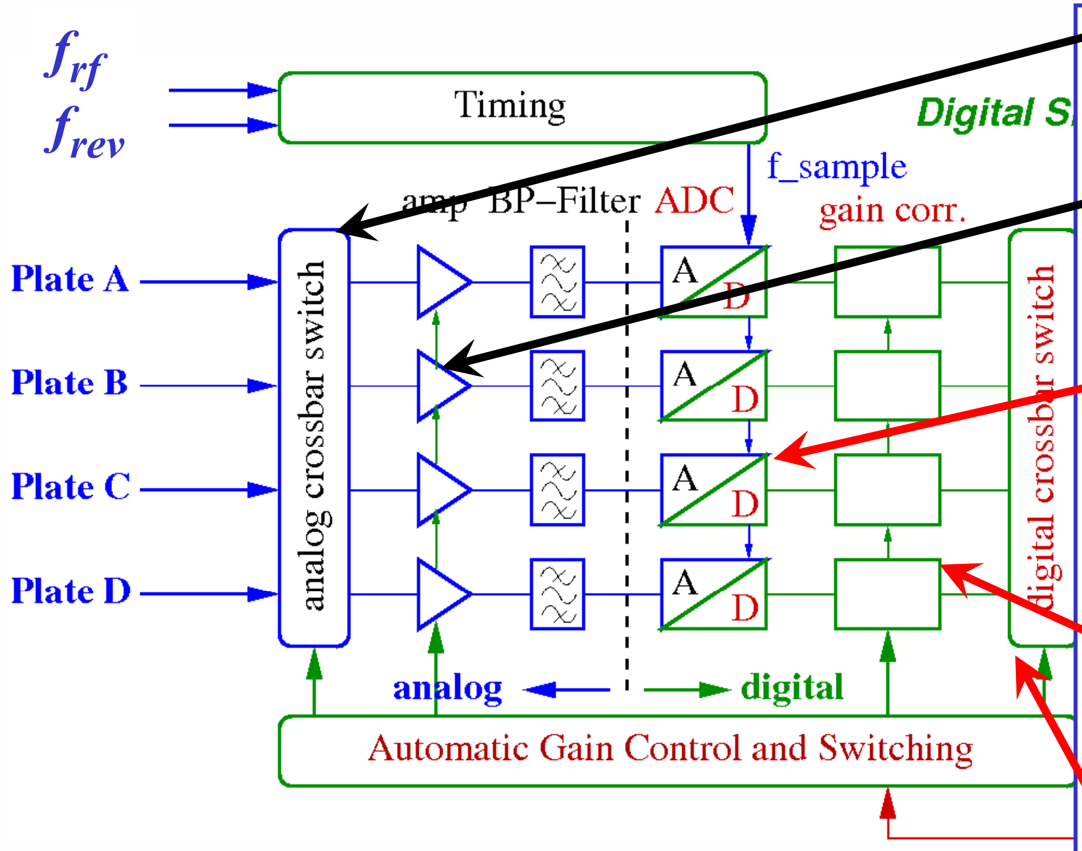


- ➢Analog multiplexing and filtering
- ➢Digital corrections and data reduction on FPGA

Commercially available electronics

used at many synchrotron light sources

LIBERA Digital BPM Readout: Analog Part and Digitalization



Crossbar multiplexing of **all** channels at ≈13 kHz (analog)

Automatic gain control by 0…31 dB
Filter 10 MHz@f_{rf} (analog)

Digitalization with ≈117 MHz
matched to sub-harmonics of f_{rf}
⇒ Undersampling: every 4th bunch

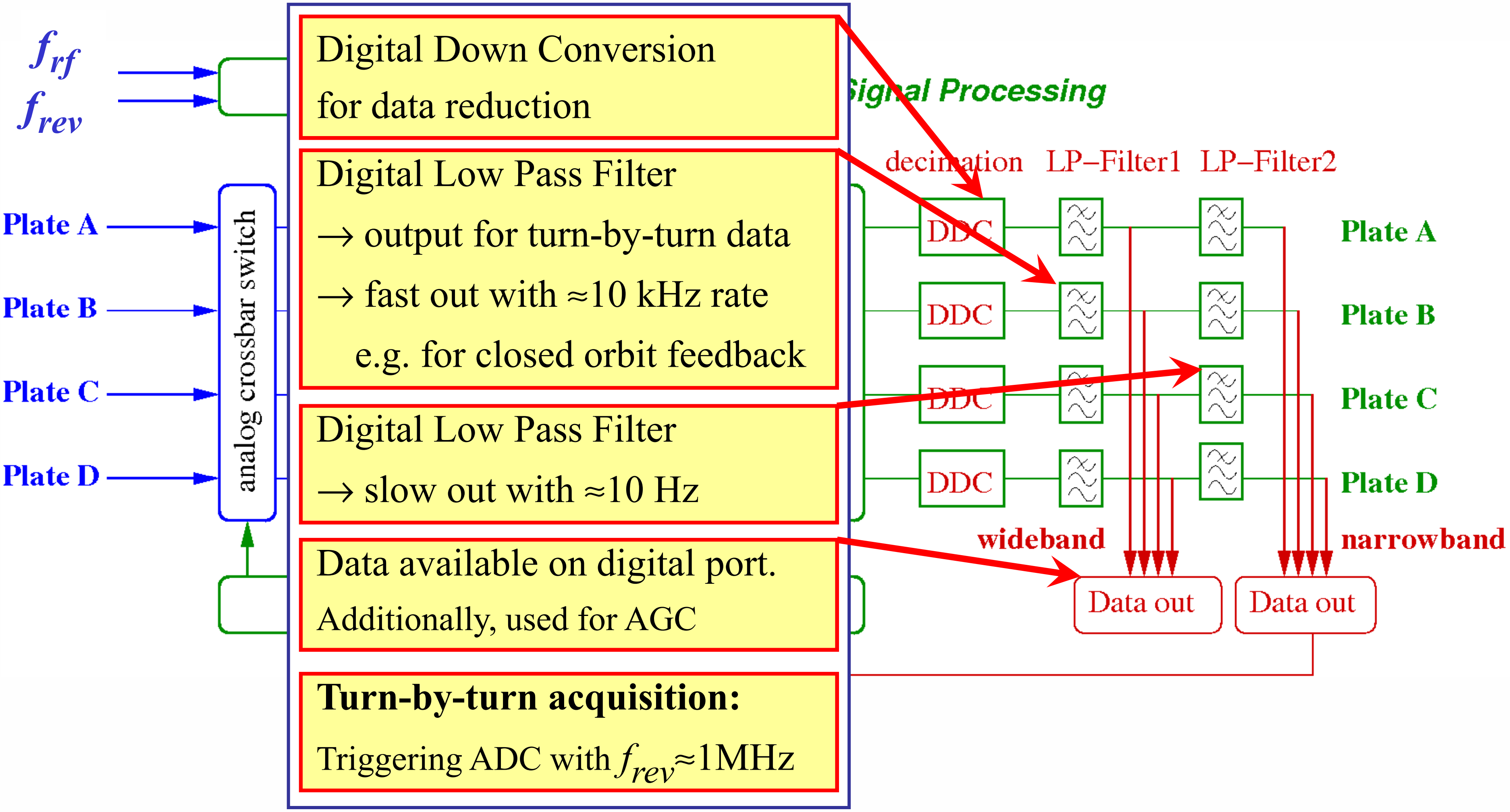
Digital compensation of amplification variation

Digital de-multiplexing

Typical values for a Synchrotron Light Source:

f_{rf}=352 or 500 MHz, revolution f_{rev}≈1 MHz

LIBERA Digital BPM Readout: Digital Signal Processing



Digital Down Conversion
for data reduction

Digital Low Pass Filter
→ output for turn-by-turn data
→ fast out with ≈10 kHz rate
e.g. for closed orbit feedback

Digital Low Pass Filter
→ slow out with ≈10 Hz

Data available on digital port.
Additionally, used for AGC

Turn-by-turn acquisition:
Triggering ADC with $f_{rev} \approx 1$MHz

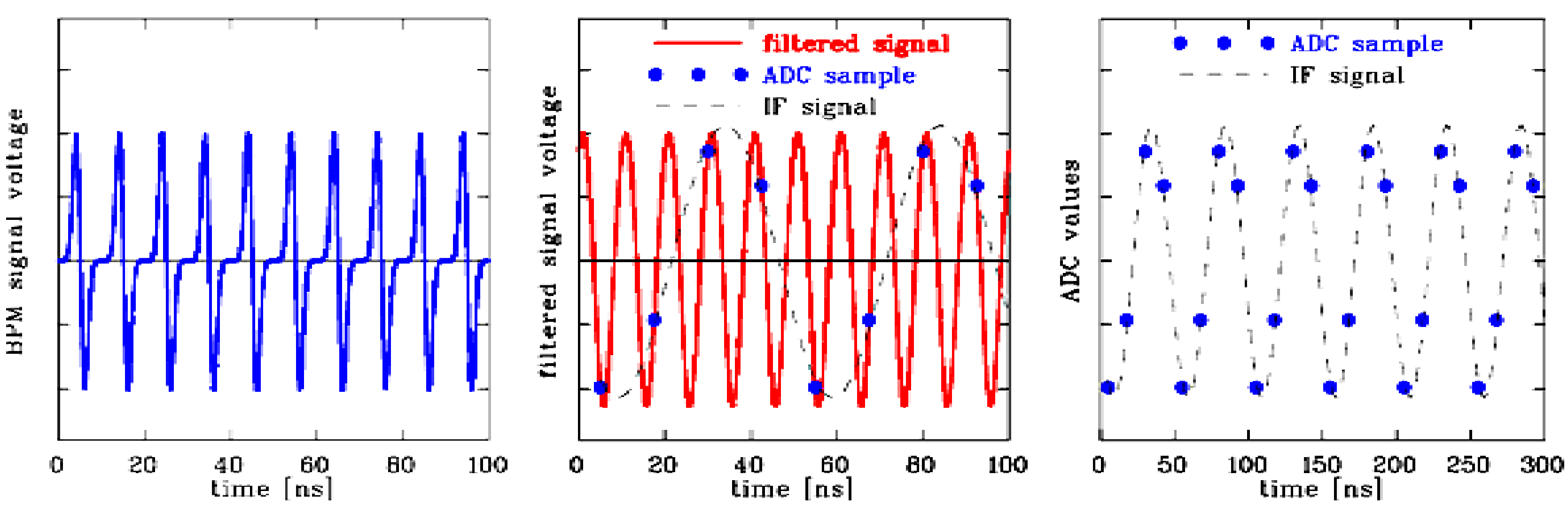
Remark: For p-synchrotrons direct 'baseband' digitalization with 125 MS/s due to $f_{rf} < 10$ MHz

Digital BPM Readout: Undersampling

Typical acc. frequency f_{rf}=500 MHz ↔ ADC sampling typ. 125 MSa/s with 14 bit

⇒ not every bunch is sampled i.e. **undersampling**

However, reconstruction of periodic signal by sampling $f_{sample} = \frac{4}{4n+1} \cdot f_{rf}$ with $n = 1,2,..$



Plotted example: f_{rf}=100 MHz ⇒ f_{sample}= 4/5·f_{rf}= 80 MHz

→ periodicity: four samples over five bunches

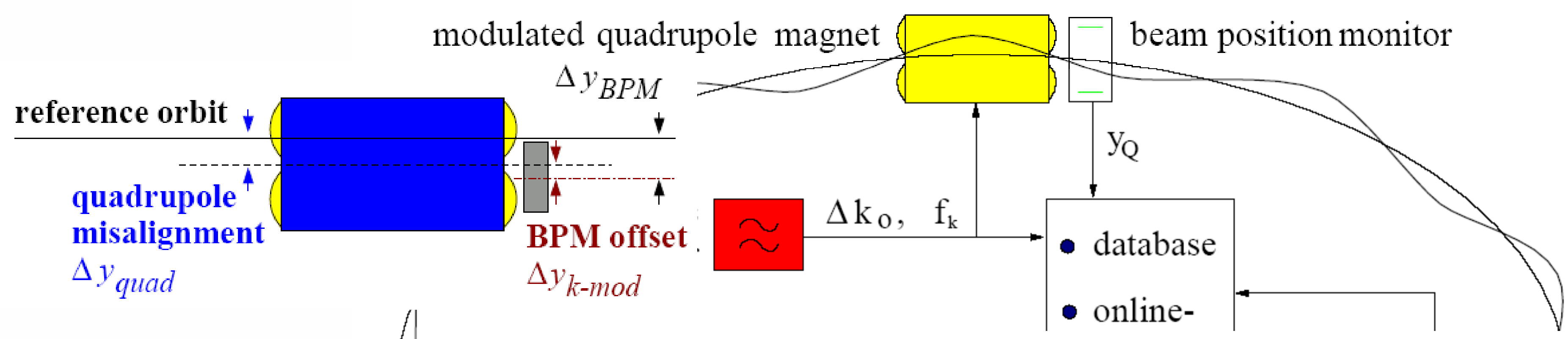
Remark: Digital broadcasting is based on undersampling and digital signal processing.

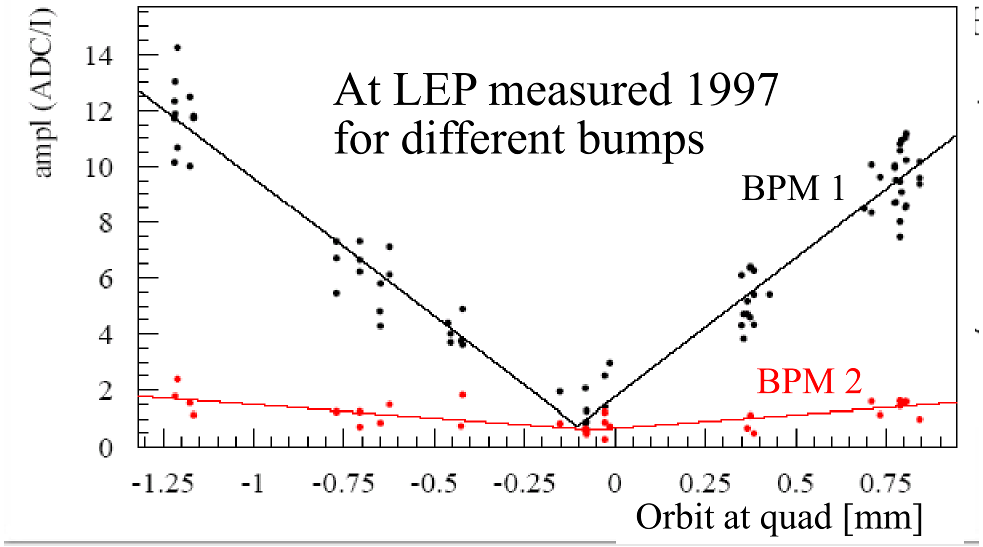
Comparison of BPM Readout Electronics (simplified)

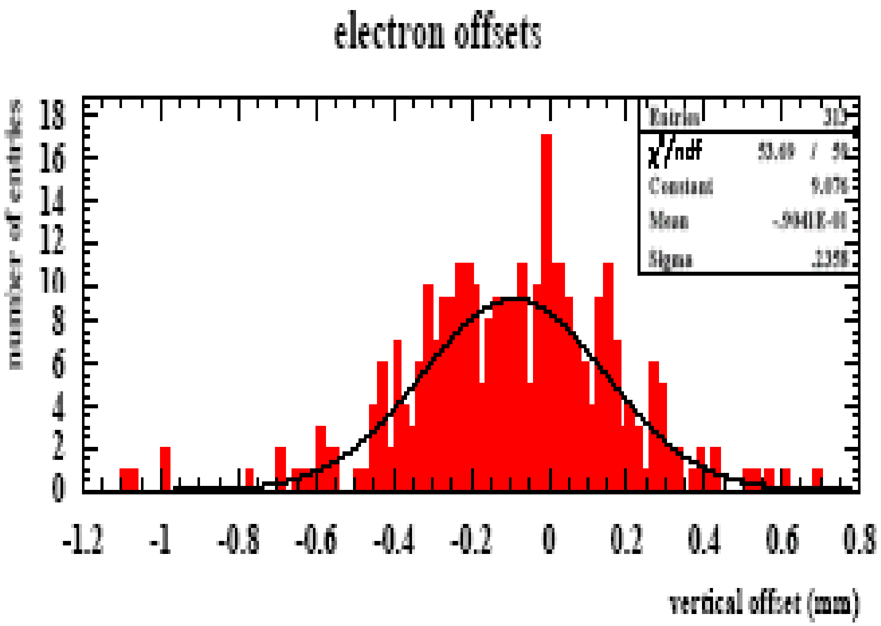
Type	Usage	Precaution	Advantage	Disadvantage
Broadband	p-sychr.	Long bunches	Bunch structure signal Post-processing possible Required for fast feedback	Resolution limited by noise
Log-amp	all	Bunch train >10μs	Robust electronics High dynamics Good for industrial appl.	No bunch-by-bunch Possible drifts (dc, Temp.) Medium accuracy
Narrowband	all synchr.	Stable beams >100 rf-periods	High resolution	No turn-by-turn Complex electronics
Narrowband +Multiplexing	all synchr.	Stable beams >10ms	Highest resolution	No turn-by-turn, complex Only for stable storage
Digital Signal Processing	all	Several bunches ADC 125 MS/s	Very flexible High resolution **Trendsetting technology for future demands**	Limited time resolution by ADC → undersampling (complex or expensive)

Remark: Calibration of BPM Center by k-Modulation

The **accuracy** can be improved by ‘k-modulation’
→alignment of the BPM with respect to the axis of the quadrupoles




At LEP measured 1997
for different bumps



Beam Position Monitors:
Detector Principle, Hardware and Electronics

Outline:

- *Signal generation → transfer impedance*
- *Consideration for capacitive shoe box BPM*
- *Consideration for capacitive button BPM*
- *Other BPM principles: stripline → traveling wave*
  inductive → wall current
  cavity → resonator for dipole mode
- *Electronics for position evaluation*
- ***Some examples for position evaluation and other applications closed orbit, tune, bunch capture, energy at LINAC***
- ***Summary***

Close Orbit Measurement

Detected position on a analog narrowband basis → closed orbit with ms time steps

Example from GSI-Synchrotron:

DSA1:[OPER.EXE.AXP]POSITION.EXE;370

Position S3 V370 HFS S08 $^{238}U^{73+}$ 1000.000 MeV/u

8. Aug 01 15:33:10

VrtAcc A 8

Gain [dB] A 20

Meßzeit 249.7[ms]

Modus Messung

Sonde alle

Soll-Delay: 10.000 ms Rampenlänge: 1578.00 ms Flattoplänge: 4509.00 ms

Start Messung 15:32:48

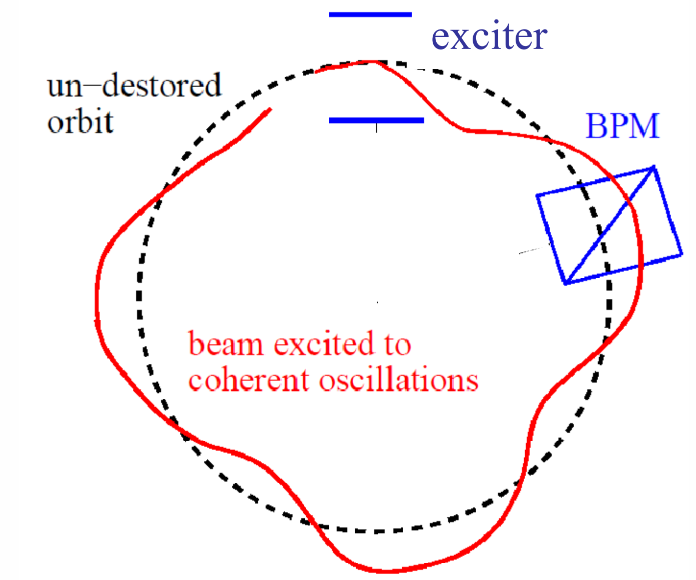
S12DX ok	S01DX ok
S02DX ok	S03DX ok
S04DX ok	S05DX ok
S06DX ok	S07DX ok
S08DX ok	S09DX ok
S10DX ok	S11DX ok

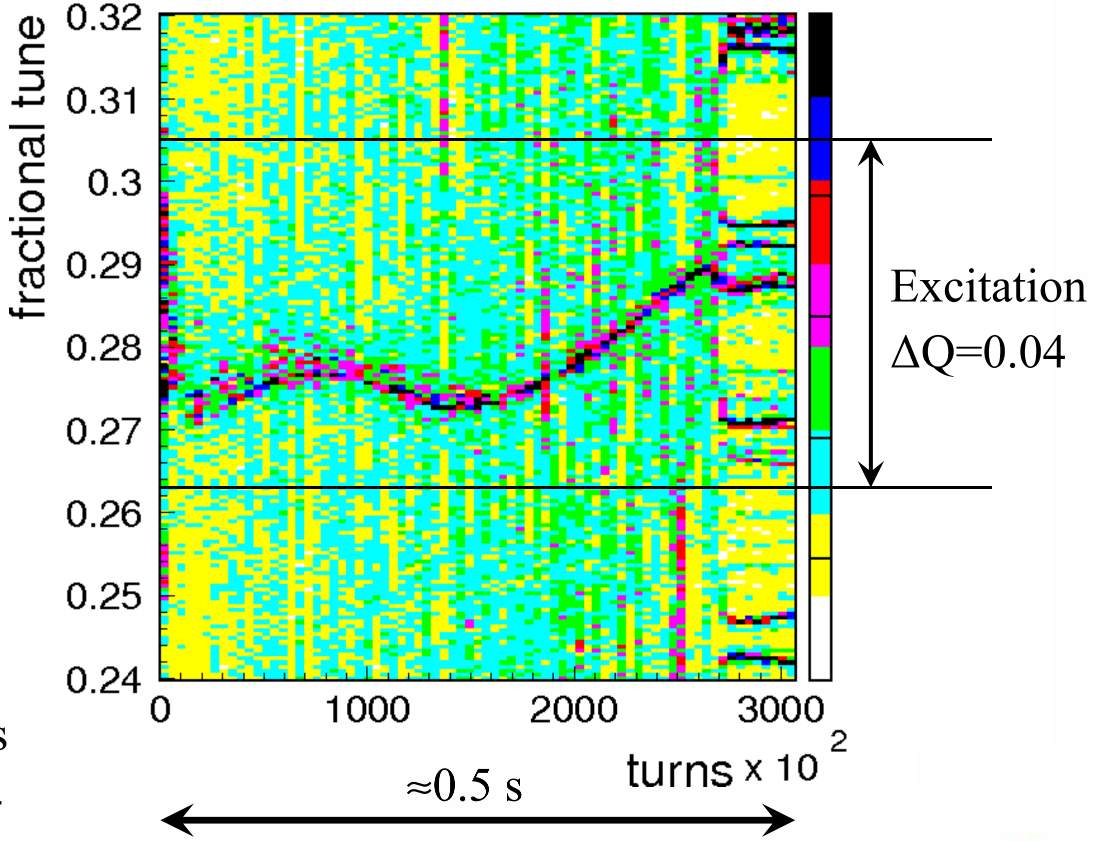
Tune Measurement by *gentle* wideband Excitation

Detecting the bunch position on a **turn-by-turn** basis the tune can be determined:

Fourier transformation of position data

→ tune within 2048 turns corresponding ≈5 ms time resolution





Beam parameters at GSI Synchr.:

U^{73+}: 11 → 250 MeV/u within 500 ms

Noise excitation corresponds ΔQ=0.04

Excitation power: only 1.5 W

Low Current Measurement on a relative Basis

The sensitivity of a BPM **Σ-signal**

by **narrowband processing**

is higher as for a dc-transformer

(with ≈1 μA on 1 kHz bandwidth).

Sum-Signal after mixing with f_{rf}:

I_{beam}>10 nA on 1 kHz bandwidth

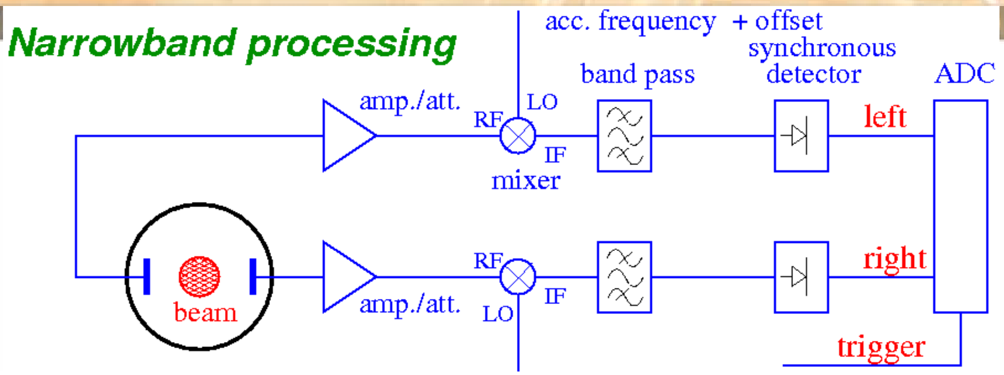
But:

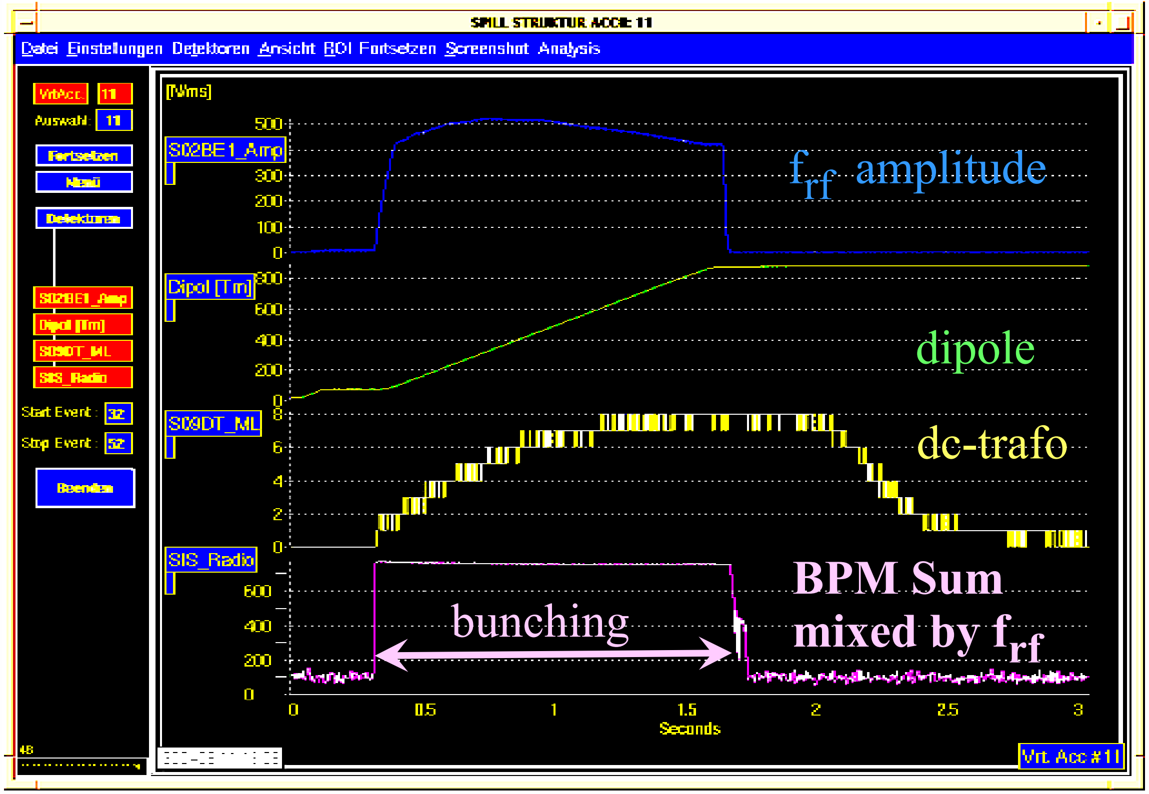
- Only for bunched beams
- Only relative measurement:

→ Signal strength depend on bunch shape i.e. frequency component!

Beam parameter: U^{73+},

11 MeV/u →1 GeV/u



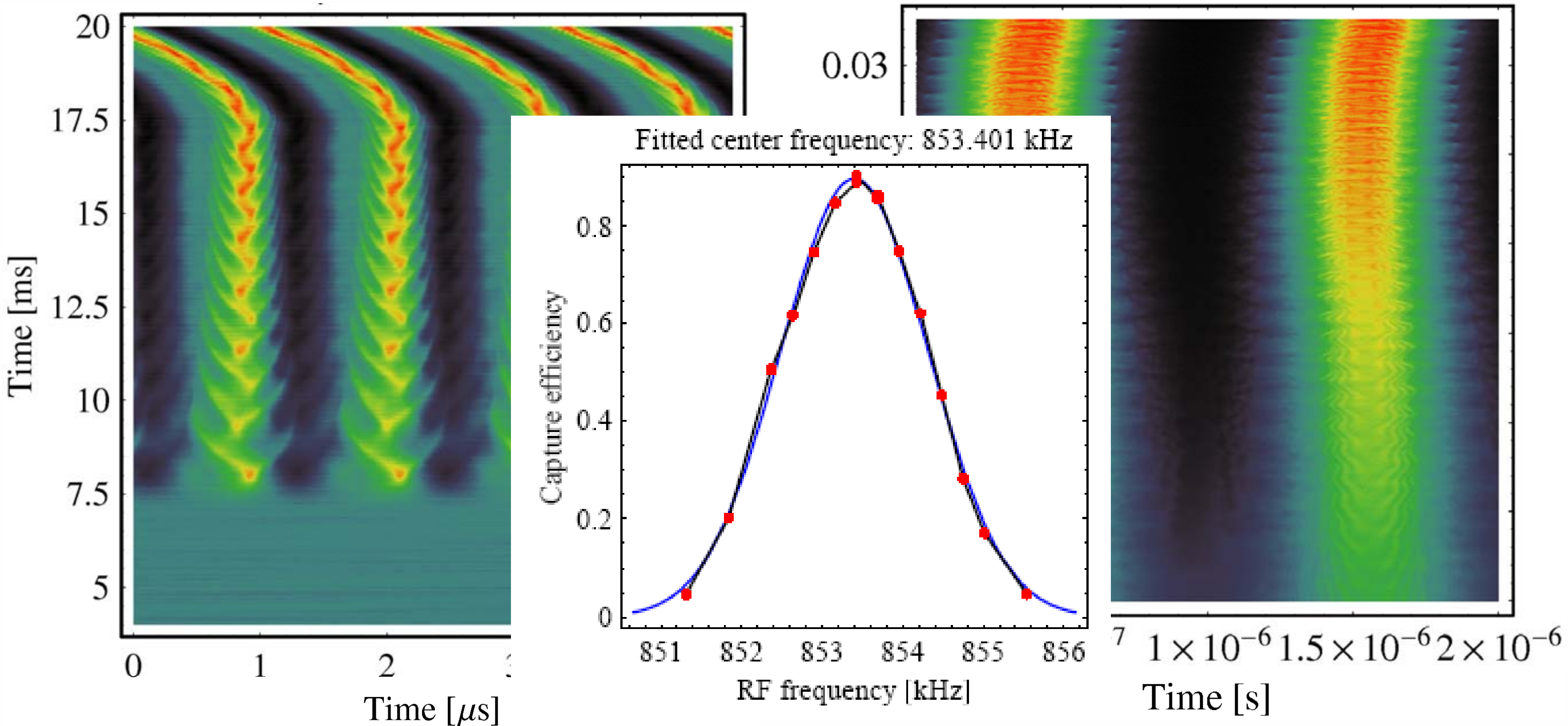


Example for longitudinal Bunch Shape Observation

Example: After multi-turn injection, the **bunch formation** is critical to avoid coherent synchrotron oscillations → emittance enlargement

f_{rf} shift by 0.2% of nominal value
⇒ Coherent oscillation

Matched f_{rf} ⇒ no oscillation



Required accuracy here: Δf_{rf}=1 kHz or $\Delta f_{rf}/f_{rf}$=0.1%

Form H. Damerau, GSI

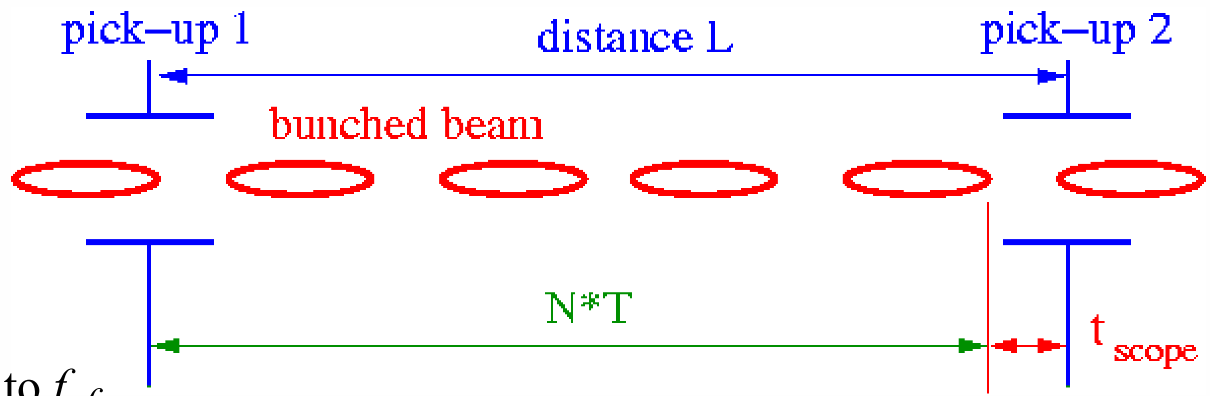
BPM for Energy Determination

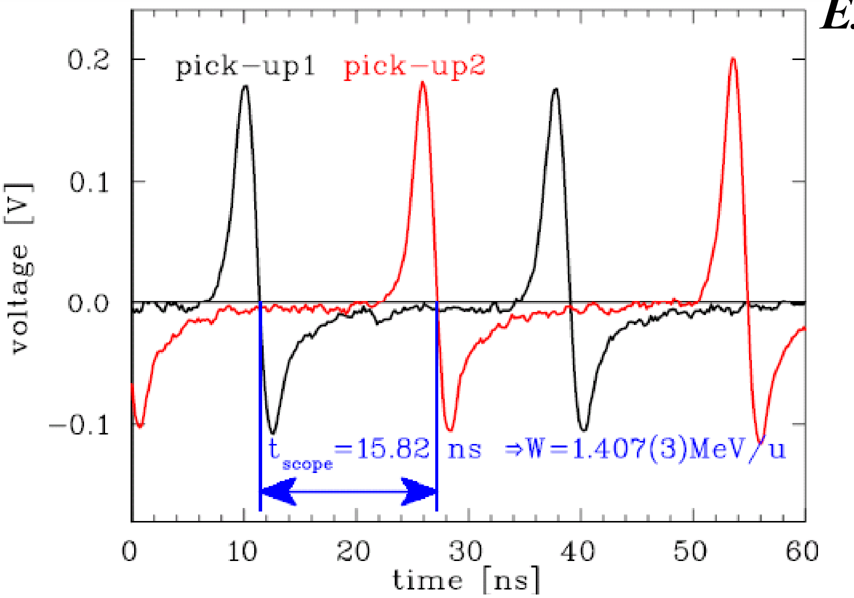
Important tool for rf-phase and amplitude alignment:

Time-of-flight measurement
with 100 ps resolution
(='phase measurement')

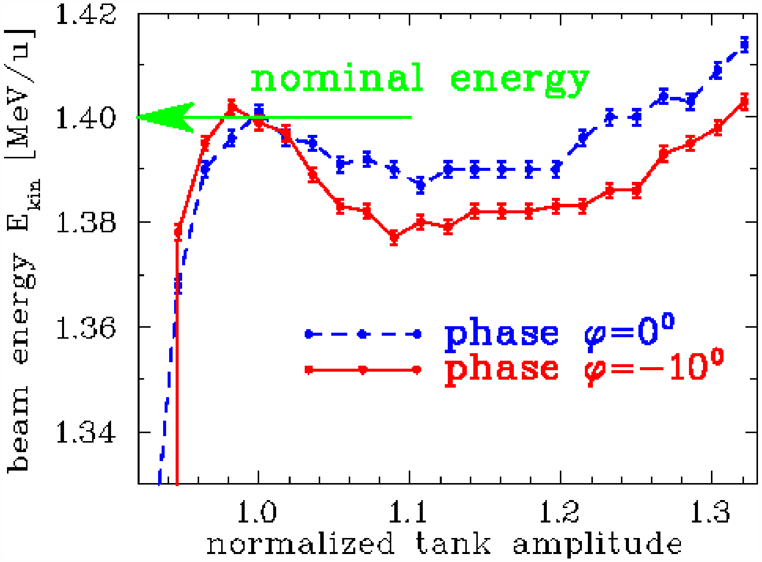
Modern system:

Digitalization
+ phase determination relative to f_{rf}





Example: TOF for 1.4 MeV/u behind IH-LINAC



Summary

With BPMs the center in the transverse plane is determined for bunched beams.

Beam → detector coupling is given by transfer imp. $Z_t(\omega) \Rightarrow$ signal estimation $I_{beam} \rightarrow U_{im}$

Different type of BPM:

Shoe box = linear cut: for p-synchrotrons with f_{rf}<10 MHz

Advantage: very linear. **Disadvantage:** complex mechanics

Button: Most frequently used at all accelerators, best for f_{rf}>10 MHz

Advantage: compact mechanics. **Disadvantage:** non-linear, low signal

Stripline: Taking traveling wave behavior into account, best for short bunches

Advantage: precise signal. **Disadvantage:** Complex mechanics for 50Ω, non-linear

Cavity BPM: dipole mode excitation → high resolution 1µm@1µs ↔ spatial application

Electronics used for BPMs:

Thank you for your attention !

Basics: Resolution in space ↔ resolution in time i.e. the bandwidth has to match the application

Broadband processing: Full information available, but lower resolution, for fast feedback

Log-amp: robust electronics, high dynamics, but less precise

Analog narrowband processing: high resolution, but not for fast beam variation

Digital processing: very flexible, but limited ADC speed, more complex → state-of-the-art

References

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